Performance Evaluation of Mobility Management Protocols for the Next Generation Internet (IPv6)

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Abstract

Internet adoption has surpassed all other communication technologies before it including telephone, radio, television and personal computers. Michael Ritter of Mobility Network Systems puts it succinctly, the Internet "fundamentally provides us with instant access to all the information ever produced by the human race".

The drive for always-on Internet access has now entered the mobile domain. Mobile commerce is the next big thing after electronic commerce. The reason for this is simple, mobile computing will become the norm for the way people conduct business, and will become as ubiquitous as the devices that we now take for granted such as mobile phones, the personal computer and a menagerie of other commonplace devices that were considered a luxury only a few years ago.

The landscape of today's telecommunications portrays an amazing patchwork of heterogeneous networks, with very few and complex bridges between them. In this context, IP technology has emerged as a natural means of initiating network convergence as the incumbent telecommunication providers have finally admitted that using IP as the foundation for next-generation mobile networks makes strong economic and technical sense.

This drive towards an all-IP infrastructure has already started with the 3rd Generation (3G) mobile networks, which is aimed at heterogeneous access devices connected to the same global network, the Internet. Mobile IP (MIP) is the current method of Internet connectivity for mobile devices. It allows a mobile device to maintain established communication sessions whilst roaming in different parts of the Internet. There are two problems with this approach, the limited address space of IPv4 and the "cumbersome communications process".

Mobile IPv6 is a current "work in progress" by the Internet's standardisation body the IETF. It solves some of the inherent limitations of MIP. However Mobile IPv6 (MIPv6) still faces the same difficulties when handling real time traffic arising from multimedia rich applications. The problems stem from the lengthy handover process at the network layer. There are some handover improvement techniques that aim to reduce the lengthy handover process.

This research is aimed at evaluating some of these techniques by simulation to see how close we are to the ideal goal of attributing handover delay to the limitations of the physical hardware below the network layer.

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Above all I am GRATEFUL to you LORD for you have never forsaken me.

Declaration

I declare that, to the best of my knowledge, the research described herein is original except where the work of others is indicated and acknowledged, and that the thesis has not, in whole or in part, been submitted for any other degree at this or any other university.

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Glossary

end-to-end delay The time interval between a packet sent from the sender and the time it arrived at the receiver. *Page ix*

home link The link on which a mobile node's home subnet prefix is defined *Page xv*

jitter In VoIP, jitter is the variation in inter-arrival times of packets. *Page 73*

L2 handover A process by which the mobile node changes from one link-layer connection to another. For example, a change of wireless access point is an L2 handover. *Page 9*

L3 handover After an L2 handover, a mobile node detects a change in an on-link subnet prefix that would require a change in the primary care-of address. For example, a change of access router after a change of wireless access point typically results in an L3 handover. *Page 8*

round trip time The end-to-end delay plus the time taken for the receiver's reply to arrive back at the sender. *Page ix*

unicast routable address An identifier for a single interface such that a packet sent to it from another IPv6 subnet is delivered to the interface identified by that address. Accordingly, such an address must have either a global or site-local scope but not link-local. *Page xiv*

List of Acronyms

3G ..... 3rd Generation Mobile communication technologies with high transfer rates in the Mbps range and the promise of global coverage.

AAA ..... Authentication, Authorisation and Accounting

AN ..... access network Provides access to the Internet.

ANG ..... access network gateway

AP ..... access point

AR ..... access router A router that exists at the edge of an access network and through which end users connect to.

ARP ..... Address Resolution Protocol

BA ..... Binding Acknowledgement

BU ..... Binding Update

CDS ..... Conceptual Data Structures

CI ..... confidence interval

CN ..... correspondent node A peer node with which a mobile node is communicating. The correspondent node may be either mobile or stationary.

CoA ..... care-of address A unicast routable address assigned to mobile node while visiting a foreign link; the subnet prefix of this IP address is a foreign subnet prefix.

DAD ..... Duplicate Address Detection

DHCP ..... Dynamic Host Configuration Protocol

DHCPv6 ..... Dynamic Host Configuration Protocol for IPv6

DRL ..... Default Routers List

DSL ..... Digital Subscriber Line

DTD ..... Document Type Definition

END-TO-END DELAY The time interval between a packet sent from the sender and the time it arrived at the receiver.

FA ..... foreign agent

FBACK..... Fast Binding Acknowledgement

FBU ..... Fast Binding Update

FHA ..... foreign home agent Any home agent that is not on the home link of the mobile node.

FMIP ..... Fast Handovers for Mobile IPv6

FSRA ..... Fast Solicited Router Advertisement

HA ..... home agent A router with extra functionality to store the location of the mobile node's current location and forwards packets to the mobile node when it is away from home.

HAWAII ..... Handoff-Aware Wireless Access Internet Infrastructure

RR ..... Regional Registration

HMIPv6 ..... Hierarchical Mobile IPv6

HoA ..... home address A unicast routable address assigned to a mobile node, used as the permanent address of the mobile node. This address is within the mobile node's home link. Standard IP routing mechanisms will deliver packets destined for the mobile node to its home link.

IANA ..... Internet Assigned Numbers Authority

ICMP ..... Internet Control Message Protocol

IEEE ..... Institute of Electrical and Electronic Engineers

IETF ..... Internet Engineering Task Force

IPv4 ..... Internet Protocol Version 4

IPv6 ..... Internet Protocol Version 6

IPSec ..... IP Security A protocol that provides authentication and encryption over the internet.

IQR ..... Inter-Quartile Range

L2 ..... Layer 2 or Data Link Layer

L2 Trigger .. link up trigger

L3 ..... Layer 3 or Network Layer

LCoA ..... local care-of address

LMA ..... Localised Mobility Agent

LMM ..... Localised Mobility Management

LT ..... Location Table

MAP ..... Mobility Anchor Point

MIP ..... Mobile IP An IETF recommendation[2] for MNs to move between IPv4 subnets without "interrupting" transport sessions in progress.

MIPv6 ..... Mobile IPv6

MIPL ..... Mobile IPv6 for Linux

MM ..... Mobility Management

MN ..... mobile node A mobile computational device that has wireless IP connectivity. Synonymous with mobile terminal (MT) and mobile host (MH) in the literature. Hereinafter referred to as mobile node for the sake of clarity.

MPLS ..... Multi Protocol Label Switching

NA ..... neigbhour advertisement

NAR ..... next access router

NAT ..... Network Address Translation

NCoA ..... new care-of address

ND ..... neighbour discovery

NIC ..... Network Interface Card

NUD ..... Neighbour Unreachability Detection

ODAD ..... Optimistic Duplicate Address Detection

OMNeT++ ... Objective Modular Network Testbed in C++

PAR ..... previous access router

PCoA ..... previous care-of address

PCoAF ..... Previous care-of address Forwarding

PCS ..... Personal Communication System

PDU ..... Protocol Data Unit

PrRtAdv ..... Proxy Router Advertisement

QoS ..... Quality of Service

RA ..... Router Advertisement

RBU ..... Regional Binding Update

RCoA ..... regional care-of address

RFC ..... Request For Comments

RO ..... Route Optimisation

RS ..... Router Solicitation

RtSolPr ..... Router Solicitation for Proxy

SIP ..... Session Initiation Protocol

TE ..... Traffic Engineering

UDP ..... User Datagram Protocol

UML ..... User Mode Linux

VoIP ..... Voice over IP A protocol for encoding and transmitting voice as IP packets.

WLAN ..... Wireless Local Area Network Refers to medium range wireless communications, typically less than 300 metres[3].

XML ..... eXtensible Markup Language

Chapter 1

Introduction

Internet adoption has surpassed all other communication technologies before it including telephone, radio, television and personal computers [4]. Figure 1.1 supports this observation. Australia's own Internet traffic has been growing at an astounding rate: for the six month period ending September 2002 there was an increase of 28% in data downloaded, and as compared to the previous six month period it was a 42% increase [5]. Michael Ritter of Mobility Network Systems puts it succinctly, the Internet "fundamentally provides us with instant access to all the information ever produced by the human race" [6].

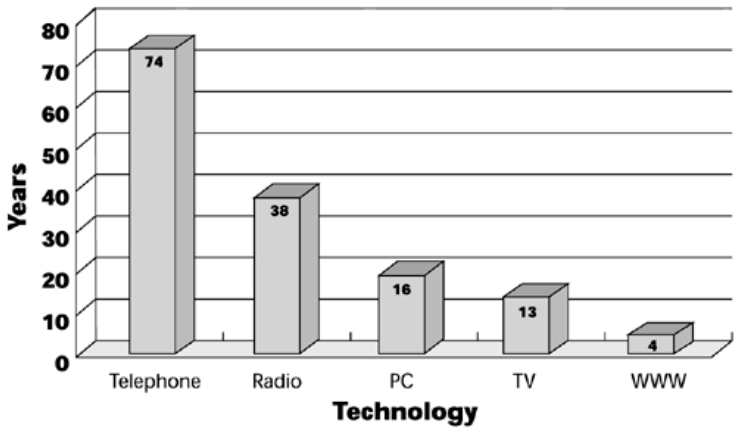


Figure 1.1: Years to reach 50 million users worldwide. (Reproduced from [1].)

The drive for always-on Internet access has now entered the mobile domain. Mobile commerce is the next big thing after electronic commerce [7, xv-xxi], because these services should be accessible from anywhere, not just some fixed location like your bedroom, school computer lab or Internet Cafe. Picture this scenario where you are to meet a client at 2pm but you are not familiar with this section of the city. It is 1:50 now. If you were sitting in front of your computer you would be able to leverage the computing and communication resources in the form of location based services to locate the meeting place. However, these services are not available at the time and place when you need them.

> Mobile commerce is important because this technological revolution will directly or indirectly affect in a significant way practically every person in the industrialised world [7, xv-xxi].

The reason for this is that mobile computing will become the norm for the way people conduct business, and will become as ubiquitous as the devices that we now take for granted such as mobile phones, the personal computer and a menagerie of other commonplace devices that were considered a luxury only a few years ago.

The landscape of today's telecommunications portrays an amazing patchwork of heterogeneous networks, with very few and complex bridges between them. In this context, IP technology has emerged as a natural means of initiating network convergence as the incumbent telecommunication providers have finally admitted that

> using IP as the foundation for next-generation mobile networks makes strong economic and technical sense, since it takes advantage of the ubiquitous installed IP infrastructure, capitalises on the Internet Engineering Task Force (IETF) standardisation process, and benefits from both existing and emerging IP-related technologies and services [8].

This drive towards an all-IP[1] infrastructure has already started with the 3G mobile networks, which is aimed at heterogeneous access devices connected to the same global network, the Internet [9].

Mobile IP [2] is the current method of Internet connectivity for mobile devices. It allows a mobile device to maintain established communication sessions whilst roaming in different parts of the Internet. However, there are two major shortcomings when faced with the continual proliferation of mobile devices seeking access to the Internet. According to Jyrki Halttunen, vice president for Nokia Networks Asia-Pacific, "more mobile phones than computers will connect to the Internet this year (2003)" [10]. The first problem is the limited address space of IPv4 [10, 11, 12]. The second problem is the "cumbersome communications process" [10, 8].

The issue of limited address space has been addressed by the gradual transition to the Next Generation Internet also known as Internet Protocol Version 6 (IPv6) [13, 14]. IPv6 has an expanded address space.

> 340 undecillion (340×10^{36}) unique addresses which translates to approximately 6.5×10^{24} addresses per square meter of Earth [15].

This is not its only advantage: it supports integrated security and prescribes IP Security (IPSec) as the Public Key Infrastructure protocol for distribution of keys. NTT in Japan is already offering dual stack Internet access [15] and full support for IPv6 exists in common operating systems such as Microsoft Windows XP™, Linux™, and the Sony Playstation™.

Mobile IPv6 is a current "work in progress" by the Internet's standardisation body the IETF [16]. It solves some of the inherent limitations of MIP as described in Section 2.2. However MIPv6 still faces the same difficulties when handling real time traffic arising from multimedia rich applications. The problems stem from the

[1] Basically a network that contains IP-based transport, multimedia services, and the integration of IETF protocols such as *Mobile IP* for wide-area mobility, Session Initiation Protocol (SIP) for signalling, and Diameter for Authentication, Authorisation and Accounting (AAA) [8].

lengthy handover process at the IP layer i.e. layer 3 in the TCP/IP protocol stack as shown in Figure 1.2. The mobile node (MN) is unable to communicate during

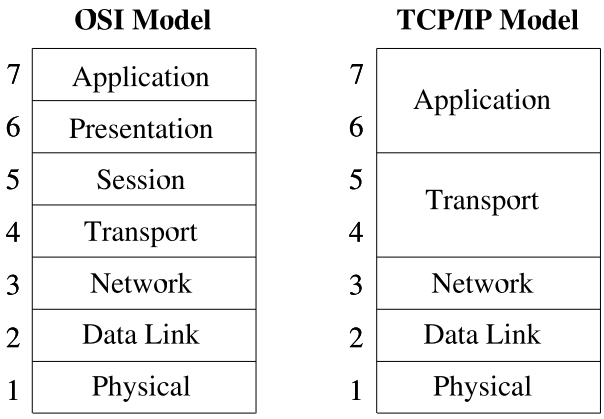


Figure 1.2: Internet Protocol Stack

handover with its peer because any packets sent to the MN at this stage are unable to reach it since the MN is no longer at its previous location. Nor can the MN send packets to its peer as it needs to acquire a new IP address before it can notify the peer node with its new location. The longer the handover process, the greater the number of packets dropped. There are some handover improvement techniques that aim to reduce the lengthy handover process. This research is aimed at evaluating some of these techniques by simulation to see how close we are to the ideal goal of attributing handover delay to the limitations of the physical hardware below the IP layer.

By solving the problem of IP mobility for multimedia and real time applications, we will be one step closer to fulfilling the promise of nomadic computing[2] as described by Kleinrock [17] and also the grand vision of pervasive computing [18], a natural extension to the culmination of computing and communications, where intelligent devices are embedded in a non-intrusive manner in our everyday surroundings, working collectively to provide us with advanced services.

[2]A personalised and customised service available anywhere, on any terminal or via any access technology.

The next chapter provides a detailed view of Mobile IPv6, as that is the IETF endorsed standard for mobility support in the Next Generation Internet. It introduces the problem of the lengthy delay in IP handover, and is followed by a more thorough treatment at the start of Chapter 3. The following two chapters describe the prospective solutions in the current literature: Chapter 3 is a survey of some access router localised handover extensions, and Chapter 4 is a survey of current Localised Mobility Management (LMM) protocols. Chapter 5 introduces the simulation model, and how the various simulation scenarios are setup to evaluate the performance of MIPv6 together with AR-local handover extensions and Hierarchical Mobile IPv6 (HMIPv6), a specific LMM solution. Chapter 6 analyses and discusses the simulation results. Chapter 7 concludes this thesis with some recommendations for future research.

Chapter 2

Mobile Internet Access

To send packets in the Internet, you need to know who to send them to. This is analogous with sending a letter to a friend where you have to know their address [19]. The IP address serves as a unique endpoint identifier for a node on the Internet and is used by Internet applications to specify who to establish a communication session with. Generally speaking the routing of packets on the Internet is also dependent upon the IP address of the destination as shown in Figure 2.1. Part of that IP address, its prefix specifies the subnet that the node exists on and routers use this information to determine the next hop for the packet. Thus an IP address also serves as a location identifier to enable packets to be routed. Whenever a node moves to a different point of attachment i.e. different subnet it is assigned with a different address to reflect its new location. The node is no longer associated with its original IP address and packets destined for the original IP address are lost.

To cater for terminal mobility the idea of visited domains was introduced from mobile telephony, and so Mobile IP [2] as ratified by the IETF in Request For Comments (RFC) 2002 came into existence. This protocol differentiates between the roles of the location and endpoint identifiers. The endpoint identifier is the home address (HoA) which acts as a node's permanent address. When the MN moves to a different subnet as shown in Figure 2.2 it will acquire a care-of address (CoA) that

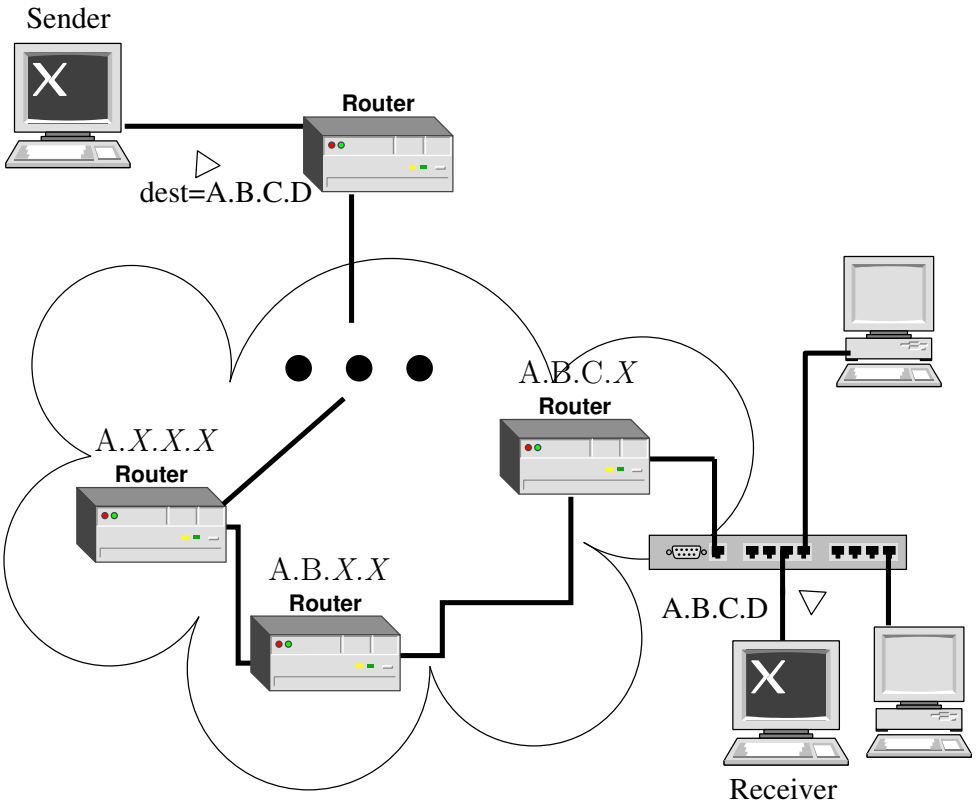


Figure 2.1: Routing on the Internet is dependent on the destination IP address to act as a unique identifier

serves as its location identifier. After acquiring the CoA, the MN will register the CoA with the home agent (HA). Any packets that were going to the HoA will now be intercepted by the HA and tunnelled to the MN at its new location. Thus Mobile IP solved the mobility issue by allowing nodes to always be reachable no matter where their point of attachment to the Internet was. To put it succinctly, the problem of mobility has been transformed into a routing problem [20].

Mobility management consists of location management which includes address management and handover management [21]. Location management is concerned with acquiring the topologically correct address (CoA) and updating the current location of the MN with the mobility agent (HA). Handover management is involved with algorithms that determine when to handover to a new location depending on

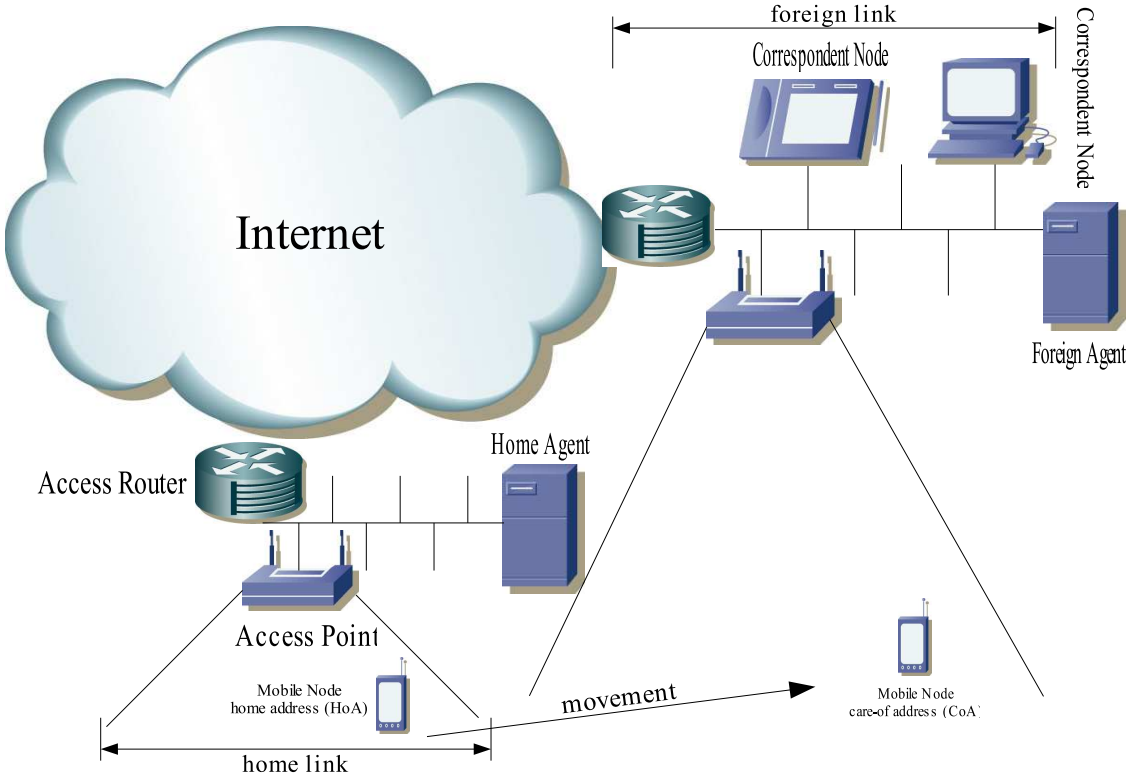


Figure 2.2: Mobile IP entities

different conditions like missed router advertisements[1], differing advertised network prefix and L2 triggers[2] [22]. Handovers can occur at either layer two or layer three. An Layer 2 or Data Link Layer (L2) handover[3] as shown in Figure 2.3, occurs when the two access points are connected to the same interface on an AR via a switch or hub. This only involves link segment specific handover procedures e.g. re-authentication with a new base station in Institute of Electrical and Electronic Engineers (IEEE) 802.11b. In an L3 handover [4] there is a change in the point of attachment to a different subnet and hence either a different AR or different interface in the same AR. The result is the acquisition of a new IP address which becomes the node's new CoA. The L3 handover is the same[5] regardless of the link

[1] the only mechanism defined for MIPv6
[2] based on layer 2 received signal strength threshold
[3] also known as link layer mobility
[4] also known as IP mobility
[5] in this research there is only one type of L3 handover as dictated by MIPv6

layer technology used, although certain hints from specific link layer technologies like IEEE 802.11b can help to reduce handover times as demonstrated in [23]. An L3 handover always implies an L2 handover as shown in Figure 2.4 although the reverse is not always true. For further details on the components of an L3 handover please turn to Chapter 3.

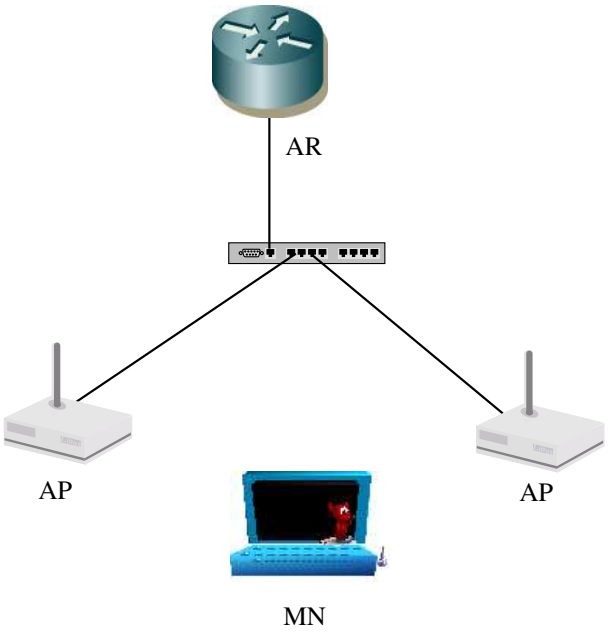


Figure 2.3: Layer two handover scenario

2.1 Mobility Support for IPv4

MIP works at the network layer of the TCP/IP protocol stack. It requires mobile agent functionality in the network provided by a server with home agent (HA) functionality on the home subnet and a similar entity known as a foreign agent (FA) in a foreign or visited subnet. These servers can be situated on routers. The MN acquires a CoA from the foreign agent (FA) or another mechanism like Dynamic Host Configuration Protocol (DHCP) can create a colocated CoA (coCoA). If using the foreign agent's CoA then packets are tunnelled by the HA to the FA while using the coCoA the tunnel reaches all the way to the MN itself. When the MN wants to send

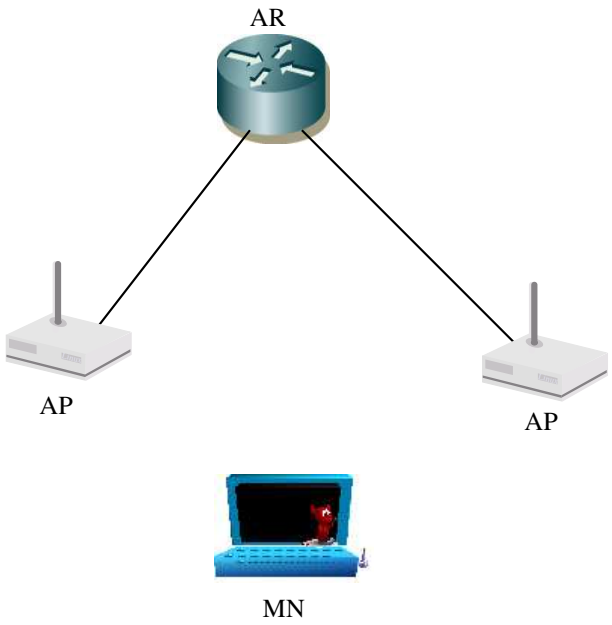


Figure 2.4: Layer three handover scenario.

a reply it will send it out directly to the correspondent node (CN) using the home address as source address. This causes the infamous triangular routing problem [24] as shown in Figure 2.5, that makes it hard for end to end Quality of Service (QoS) provisioning to work because the path travelled by the packets is not the same in both directions.

Theoretically an established connection at a site with MIP support does not break when moving to a different subnet, even one with different access technology from the transport layer's perspective. This is made possible by preserving the transport layer application's end points for communication i.e. the HoA as the network layer uses a different point of attachment.

While MIP was able to solve the problem of node mobility by assigning a permanent address to the node and mapping that to its current location in the Internet, there are performance implications to consider if seamless handovers[6] are required. Seamless handovers are required when real time traffic traverses the network.

[6] A handover in which there is no change in service capability, security, or quality. In practice, some degradation in service is to be expected [25].

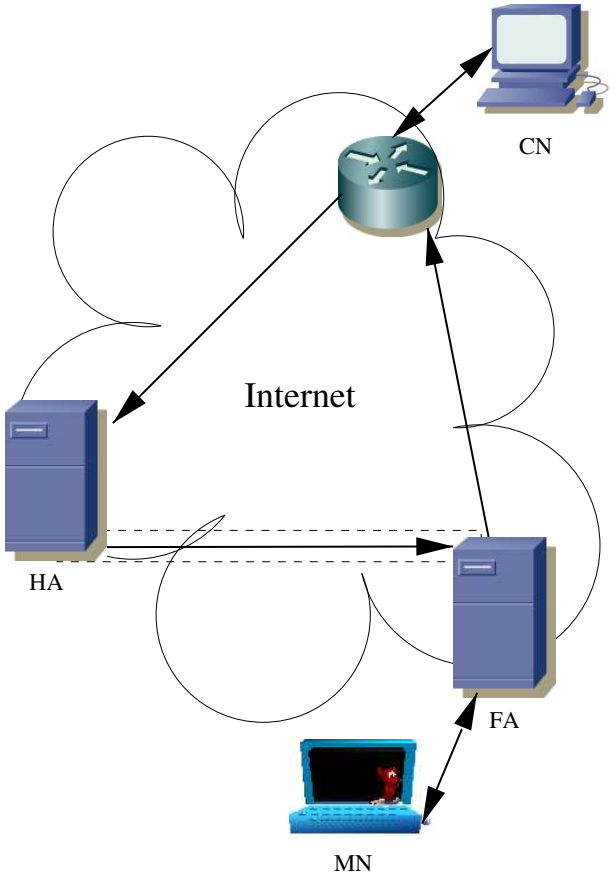


Figure 2.5: Triangular routing in MIP

Real time traffic from applications such as video conferencing and Voice over IP (VoIP) require tight bounds on end-to-end delay and packet loss. MIP's triangular routing will increase the end-to-end delay from the CN to the HA because it is the sub-optimal route. A MIP handover involves acquiring a CoA and updating mobility bindings with the HA and CNs[7] and so introduces some latency on top of the latency from the L2 handover. The effect of handover latency is to interrupt established communications momentarily, packets are dropped as a result and the user perceives a loss in quality of the multimedia stream. MIP is also very inefficient when you consider the tunnelling overhead of every packet received while the MN is away from home.

[7] route optimisation is an extension to Mobile IP

This is a very active area of research because the global mobile phone market is currently transitioning to 3G. There have been many proposals that extend MIP and alternative mobility management protocols [26, 20, 27, 28] with the aim of reducing the handover latency[8] and signalling overhead. However, the common consensus is that Mobile IPv6 (MIPv6) is the base standard for mobility in next generation IP networks [10, 8].

2.2 Mobility Support in IPv6

2.2.1 IPv6

The Next Generation Internet protocol (IPv6), is as its name suggests, the next generation protocol for the Internet that was ratified in 1995 [13]. IPv6 was created to solve the inherent limitations of the current Internet Protocol IPv4. The most publicised limitation was the uneven distribution of global IP addresses particularly favouring the United States of America[9] [12]. Consider the case of Stanford University in America has more publicly allocated IP addresses than the whole of China. According to Uti Rahamim VP of sales at Hitachi Internetworking, public IP addresses could run out as early as 2005. Dr. Paul Francis credited with the proposal for Network Address Translation (NAT) claims that NAT[10] extends IPv4 address from 32 to 48[11] bits effectively [12]. While NAT allows more people to surf the Net and view their e-mails, it fails to provide global routability. So peer to peer applications like Microsoft's NetMeeting will not work. To overcome this problem a server is needed to arbitrate between clients which defeats the purpose of peer to peer applications. NAT still does not solve the uneven distribution of global IP

[8] henceforth this term shall be taken to mean L3 handover latency unless stated otherwise

[9] over 70%

[10] also known as port mapping

[11] Theoretical maximum derived from maximum number of network ports used by NAT on a computer which is 2^{16}. It is theoretical because not all the ports can be used for NAT e.g. Internet Assigned Numbers Authority (IANA) reserved ports in the range 1-1024 inclusive, just like not all 32 bits in an IP address can form public IP addresses

addresses.

Others have felt that NAT was at best a band-aid solution and waited till something better to arrive. IPv6 has 128 bit IP addresses, and is available now. Many organisations have tried to increase the uptake of IPv6 . The EU has invested 55M Euro in a live IPv6 network such as 6Net[12] in an attempt to speed up migration to IPv6 and break the cycle of wondering whether should the network be built first to test applications or applications built first before the network rolls out, because investment in network infrastructure without applications is expensive according to Cisco's Falkner [12]. 3GPP a global standards body for 3G cellular networks has mandated UMTS Release 5 for IMS (Internet Multimedia Service) protocols operate on IPv6 only [12, 11]. Without a doubt the global transition to IPv6 is inevitable.

The following is a brief list of advantages IPv6 has over IPv4 [29]:

- larger address space 2^{128} compared to IPv4's 2^{32}
- an in-built mechanism to automatically configure the network interfaces[13] [30]
- globally unique and hierarchical addressing [31] based on prefixes rather than address classes, to keep routing tables small and backbone routing efficient[14]
- supports encapsulation of other protocols as well as itself [33]
- improved multicast routing support (in preference to broadcasting)
- built-in authentication via AH (Authentication Header) and encryption in terms of ESP (Encapsulated Security Payload) [13]
- inherent support for mobility, MIPv6 is implemented with destination options which are an integral part of IPv6 [8].

[12] www.6net.org

[13] Separate from DHCP (Dynamic Host Configuration Protocol)

[14] Instead of IPv4 having over 2 million routes in core routers you only have a maximum of 8,192 derived from the 13 bits for the TLA (Top Level Aggregation) field in an IPv6 address [32]

2.2.1.1 Address Resolution

IP addresses are abstract addresses that network administrators assign or are derived from the autoconfiguration process described in Section 2.2.1.2. Each IP address is mapped to the Network Interface Card's link-layer address which is programmed into the Network Interface Card (NIC) during manufacture and is guaranteed to be sufficiently unique. To determine the link-layer address from an IP address of a host residing on the same link, a process known as address resolution is carried out in order for packets to be delivered to the correct node.

In IPv4, the Address Resolution Protocol (ARP) operated in the data link layer of the TCP/IP protocol stack as shown in Figure 1.2. The "equivalent" functionality in IPv6 is provided by neighbour discovery which operates from the network layer and replaces ARP. This mechanism is defined in RFC 2461 Neighbour Discovery of IPv6 [34]. Neighbour discovery as its name implies, is for determining the existence of neighbouring hosts on the local subnet and their corresponding link-layer addresses.

When a node A wants to send a packet to node B on the same link as shown in Figure 2.6, it will send a neighbour solicitation. This packet is addressed to a special multicast group formed from B's IP address. This is known as the solicited multicast address [31]. The packet contains A's link-layer address in the source link-layer address option. This allows B to send a unicast neighbour advertisement back to A. Node A will wait for B's neighbour advertisement for at least MAX_MULTICAST_SOLICIT[15]*RetransTimer seconds with a neighbour solicitation resent when RetransTimer[16] seconds have elapsed. When B receives the multicast neighbour solicitation, it will put its link-layer address into a target link-layer address option and place that into a neighbour advertisement to be sent directly back to A. Before A receives the neighbour advertisement any other packets that are destined for B will be placed into a queue for packets that are pending address

[15] default three times [34]
[16] default of one second [34]

resolution to B. After the neighbour advertisement arrives at A, A can send all the pending packets in the queue and adds the link-layer address mapping to B's IP address to the neighbour cache. Any future packets addressed to B's IP address will find B's link-layer address directly from the neighbour cache.

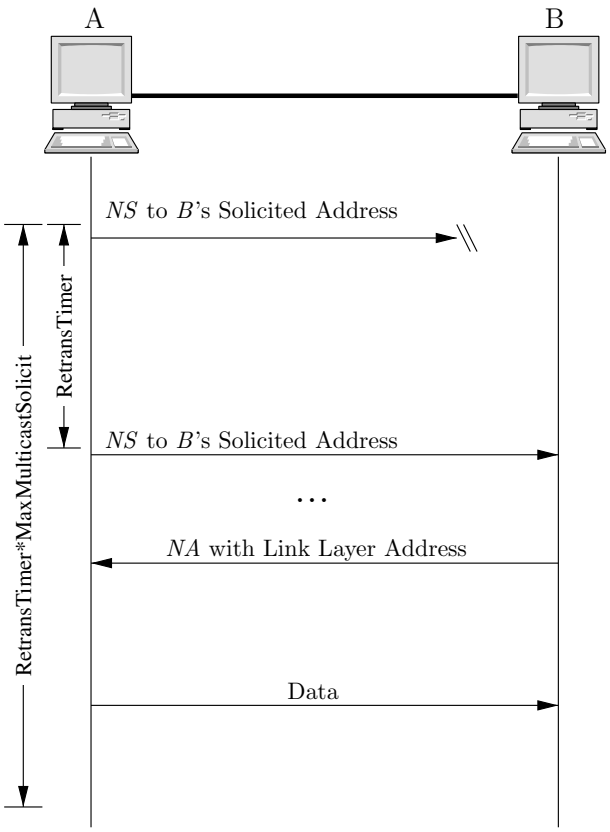


Figure 2.6: IPv6 address resolution operation

2.2.1.2 Autoconfiguration

IPv4 networks required either a network administrator or the presence of a DHCP server to assign an IP addresses. IPv6 has a configuration mechanism implemented by all conforming nodes called Stateless Address Autoconfiguration [30] that allows a node to automatically assign a suitable address for itself.

Autoconfiguration consists of two processes Duplicate Address Detection (DAD) and Router Discovery. A node is able to self configure based on the premise that

its network interface is a unique identifier. The first address that all nodes using autoconfiguration self assign is the link-local address. This consists of a link-local prefix `FE80:0:0:0:0:0:0:0/64` [31] prepended to the interface identifier[17]. The link-local prefix is only recognised within the scope of the link which means that routers will not forward these packets. The link-local address goes through DAD first before been assigned to ensure that no other node has the same link-local address. At the same time the node can initiate router discovery in order to allow the node to start communicating as soon as DAD is finished.

The un/solicited router advertisement contains prefixes and each is inspected for the autoconfiguration flag. If this flag is set then the prefix is combined with the interface identifier to form other addresses e.g. a globally scoped address so the node can communicate on the Internet. Usually DAD is only done on the link-local address because every other address is formed from the interface identifier that has been tested to be unique on that link when the link-local address was self-assigned. Likewise the prefixes advertised by the router should be unique within their scope, because they are configured by the network administrator.

2.2.1.3 Router Discovery

The function of Router Discovery in IPv6 is to allow the non-router nodes to both solicit and process received un/solicited router advertisements. The routers will send unsolicited advertisements separated by a time interval that is uniformly distributed between MIN_RTR_ADV_INT and MAX_RTR_ADV_INT. Once a router is discovered on the network it is added to the Default Routers List (DRL). The DRL stores the list of routers that the node can forward off-link packets to. If there are no routers on the network then every address is considered to be on-link [34]. Upon reception of an advertisement by a node, the prefixes advertised by the router are searched and if the on-link flag is set for a prefix then that prefix is added to the

[17] a MAC address for Ethernet links

node's prefix list. The on-link prefixes in this list are compared against destination addresses of packets to be sent. Addresses that match the prefix are actually on-link and these packets can be sent directly to a neighbouring node without the router's intervention.

The DRL and on-link prefixes list are Conceptual Data Structures (CDS) used in the conceptual sending algorithm. It is an algorithm that all nodes use to determine how to forward or send a packet.

2.2.1.4 Encapsulation

Encapsulation is the process of putting an IPv6/4 datagram as the payload of another IPv6 datagram [33]. The purposes for doing this are many but usually it is to deliver packets to destinations that are not reachable using normal forwarding methods. Encapsulation in general involves four parties, the original source A and destination B of the packet along with the tunnel entry point C and exit point D as shown in Figure 2.7. The tunnel entry point is where the original datagram from A is encapsulated into another datagram with the source address of C and destination of D. The packet is decapsulated[18] at tunnel exit point D and forwarded to its final destination B without modification. The packet arrives at B and appears to have originated from A. B does not know that the datagram traversed the tunnel C-D. Thus encapsulation is a non invasive forwarding mechanism to supplement normal packet forwarding done by routers. A tunnel is unidirectional so to go in the reverse direction from B to A via the tunnel D-C will require the reverse tunnel D-C to be established first.

The tunnel destination D and original destination B can be the same node. An example of this occurs in MIPv6 when the HA intercepts a packet from the CN (A) destined for the MN at its HoA (B) and encapsulates it with a tunnel source of the HA's address (C) and tunnel destination of MN's CoA (D). The reverse tunnel which

[18] the original datagram is extracted from the encapsulating datagram

is a tunnel in the opposite direction where the MN is both the tunnel source (C) and the original source (A) sends a packet to the CN (B) via the HA (D). This is known as the reverse tunnelling procedure in MIPv6.

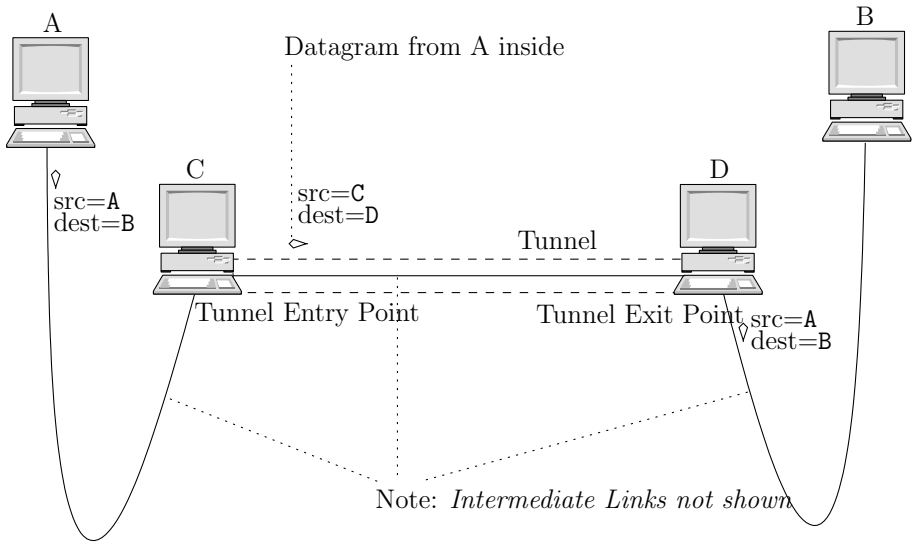


Figure 2.7: Entities involved in IPv6 Encapsulation

2.2.2 Mobile IPv6

Mobile IPv6 [16] is the same in concept as MIP without MIP's disadvantages. The advantages of MIPv6 over MIP were mentioned briefly in Chapter 1 where it was mentioned that MIP used a "cumbersome communications process". This can be seen as a reference to the triangular routing problem which was described already at Section 2.1, the use of tunnelling, and topologically incorrect source address when away from home subnet. While MIP can overcome the triangular routing problem using the reverse tunnelling procedure described above, reverse tunnelling is quite inefficient because of the overhead arising from the extra IP datagram header and the extra decapsulation and forwarding load at the HA. There is a route optimisation extension to MIP that can also eliminate triangular routing but due to the limitations of Internet Protocol Version 4 (IPv4) it still uses encapsulation [28, 8] to deliver packets to the MN directly. The topologically incorrect source address in

MIP, the HoA is used by the MN when sending packets. These packets are usually dropped because a security conscious network adminstrator will have enabled the routers' ingress filtering, so that only packets with topologically correct (according to a predetermined policy) source addresses are forwarded. All of these problems are solved by MIPv6 as explained below.

IPv6 inherently supports mobility with the autoconfiguration feature. This eliminates the need for explicit FAs on foreign links as the MN can use normal Router Advertisement (RA)s to acquire a CoA. The only change required to support MIPv6 in routers is for them to include an R bit in a prefix information option of their router advertisement. This prefix includes the router's global unicast address and is the prefix used by the MN to configure its CoA to ensure that it is globally reachable from the Internet.

There are two modes of communication in MIPv6. The default mode uses tunnelling via the HA while the preferred mode is a direct route established with a procedure called route optimisation. Both methods are shown in Figure 2.8. Unlike MIP, triangular routing is not a method of communication although this can occur momentarily during the transition phase between the two different modes.

2.2.2.1 Interception of Datagrams for Tunnelling by HA

While the MN is away from home, the HA it has a legal mobility binding with will act as its proxy. This means that any datagrams addressed to the MN will end up at the HA because the HA will respond to all neighbour solicitation requests for the MN.

Once the HA has intercepted a datagram, it will forward it to the MN at its current location, the CoA obtained from the binding cache entry for the MN. The binding cache entry was created when the MN registered with the HA and is updated by further Binding Update (BU)s from the MN. The tunnel header will have a source

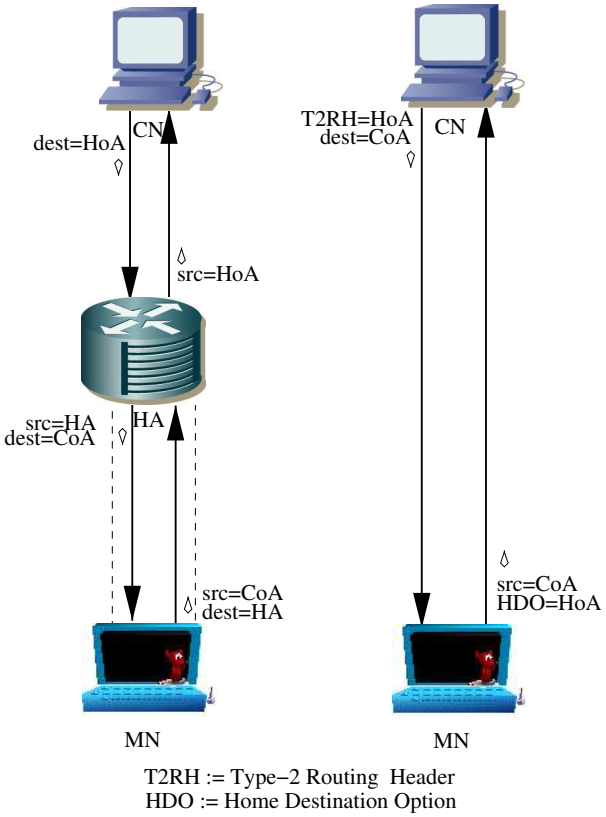


Figure 2.8: Two modes of communication in Mobile IPv6

address of the HA's global router address as advertised in its prefix information option and destination address of the MN's CoA. The MN decapsulates the datagram upon arrival resulting in the original datagram, as if the CN had sent it directly to the MN.

When an MN has not established a binding with its CN, it should send the datagrams destined to the CN via the HA using the reverse tunnelling procedure. The original datagram has a source address of HoA and destination address of the CN while the tunnel's source address is the MN's CoA and the destination is the HA's global router address. Once the HA receives this packet it will check that the tunnel's source address is indeed the CoA corresponding to the HoA from the original datagram's source address to prevent other nodes from masquerading as the MN before forwarding the original datagram. Thus when the datagram arrives at

the CN it looks like the MN had sent it from its home subnet.

2.2.2.2 Direct communication using Route Optimisation

MIPv6 does not require tunnelling between the MN and the CN when in the route optimised mode of communication thanks to the ingenious use of the home address destination option and type-2 routing header. The two are a substitute for the function of the endpoint identifier provided by the encapsulation mechanism but with the overhead reduced to a minimum. The *home address destination* option from the MN contains the home address. This allows an MN to send datagrams with a source address of CoA which is topologically correct in the foreign domain and so passes the access router's ingress filtering rules. When the datagram arrives, the CN will process the home address destination option by swapping the home address in the option with the datagram's source address. The modified datagram is passed on to the transport layer and so the application is not even aware that it is communicating with a mobile entity. A similar process occurs in reverse when the CN is to send a datagram to the MN. The application addresses the packet to the MN at its HoA. At the network layer the CN will inspect its binding cache to discover the MN's current location i.e. its CoA as reported by the last BU from the MN. It will add a type-2 routing header to the datagram with the HoA and replace the source address with the CoA. The packet will travel through the network using normal procedures and arrives at the MN. The MN will process the type-2 routing header by swapping its contents with the source address of the datagram. Thus the final datagram passed to the transport layer has HoA as the source address. This keeps applications ignorant of the node's movement.

To establish a direct route, the MN needs to send a BU to the CN containing the MN's current CoA. This will be stored by the CN in its binding cache. In order to prevent malicious nodes from masquerading as a certain MN by sending BU with HoA of the MN, the *return routability* procedure is used to verify the nodes au-

thenticity. The following explanation provides a very simplified view that omits the mathematical functions and protocol details, for further information please consult [16]. The first step is for the MN to send an initiation message to the CN to start the return routability procedure. The CN will then send a test packet on each of the two different routes, one via the HA using the HoA as destination while the other uses the CoA as destination. The two test packets contain parts of a one time cookie that are assembled at the MN and sent back to the CN. Unless the initiating node is at the location specified by the CoA is also the owner of HoA, it cannot receive both parts of the secret token. This is based on the assumption that the HA has adequately authenticated the MN's identity. This is a valid assumption as MIPv6 has mandated the use of IPSec authentication in binding updates from the MN to the HA. Thus return routability will add an extra one and a half roundtrips per CN that is to be route optimised.

When it comes to handling real time traffic MIPv6 addresses better than MIP the requirements for stringent end to end delays, because it does not use triangular routing at all and stipulates that the route optimised mode be used unless the CN is administratively prohibited from doing so. However, the requirements on packet loss are not satisfied yet due to the long handover latency of over 2 seconds [35].

Chapter 3

Access Router Localised Handover Extensions

Handover latency is defined as the interval starting from the moment when the mobile node leaves the old access medium until it resumes communication with the CN at the new access medium [36]. This is shown in Figure 3.1. There are three components to handover latency. The first D_1 is the L2 handover latency i.e. the link layer specific handover procedure. In the scenario shown it is the 802.11b handover procedure to switch to a new access point. D_2 is the time taken by the MN to detect the presence of a new AR at the new access network and configure a new CoA. This is also known as the rendezvous time delay [22]. Rendezvous time is affected by the amount of overlap or distance between the two neighbouring coverage areas of the access point (AP)s, the speed of the mobile node and the rate of unsolicited Router Advertisement (RA) beacons [8, 9]. The third component D_3 is the time it takes to send a BU back to the HA/CN and the subsequent resumption of communications indicated by a new data packet arriving at the MN from the new AR. This is also known as the registration delay.

L2 handovers are not discussed any further in this paper as they depend on the

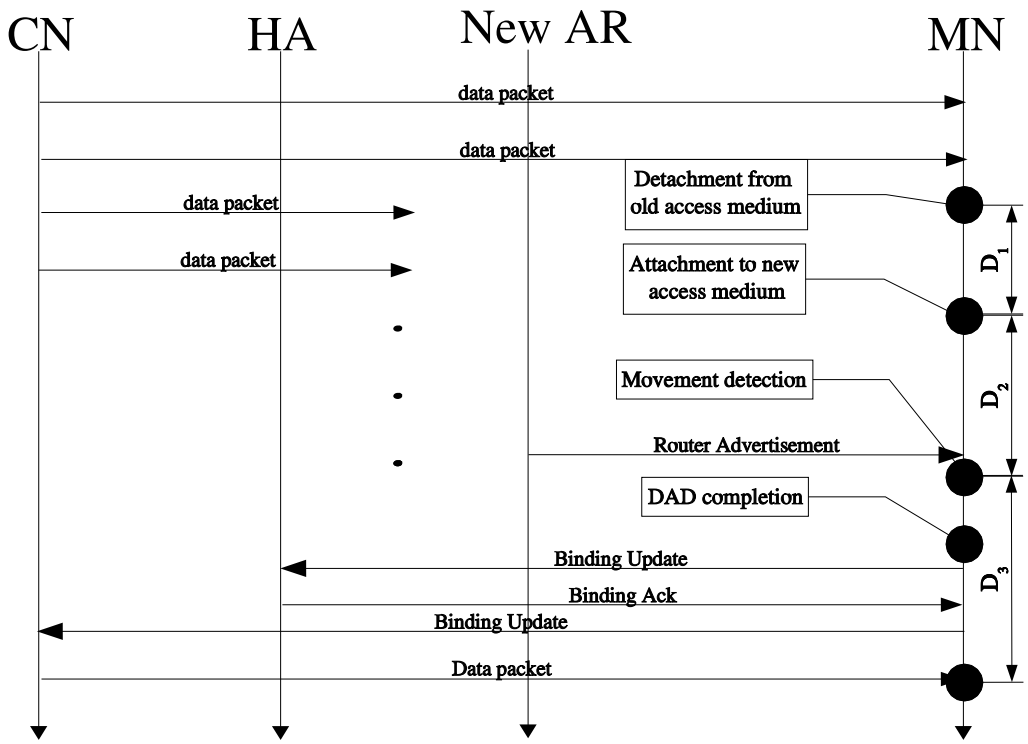


Figure 3.1: Handover latency components for Mobile IPv6

specific physical transport technology and nothing can be done to alter its behaviour at the network layer. The rendezvous time is affected by the frequency of router advertisements. Registration delay is affected by the path delay and packet loss of the path the BU takes from the MN to the HA in the Internet.

There are basically two varieties of handover management techniques, predictive and non-predictive [23]. The predictive varieties tend to require assistance from the network infrastructure, functionality that is usually not built into the system. It is predictive because it predicts which wireless link and hence subnet the MN will move to before the actual handover. Non-predictive handovers in general do not require special assistance from the wired infrastructure and are reactive in nature i.e. it will perform an L3 handover only after it has detected a transition to a different L3 subnet. As a general rule of thumb predictive handovers are much more complex to implement and manage.

3.1 Fast Handovers for Mobile IPv6

An example of a predictive handover technique is Fast Handovers for Mobile IPv6 (FMIP) [37]. It can reduce both the rendezvous and registration delay by anticipating handover before it happens and carrying out some of the time consuming operations before the actual L2 handover occurs. This requires modifications to the ARs. FMIP forms a temporary tunnel between the previous access router (PAR) and the next access router (NAR), thereby allowing the MN to receive packets at the NAR's access network before the MN has finished its registration and established itself with the NAR. There are three stages to this process: handover initiation, tunnel establishment and packet forwarding, abbreviated as HI, TE and PF respectively in Figure 3.2.

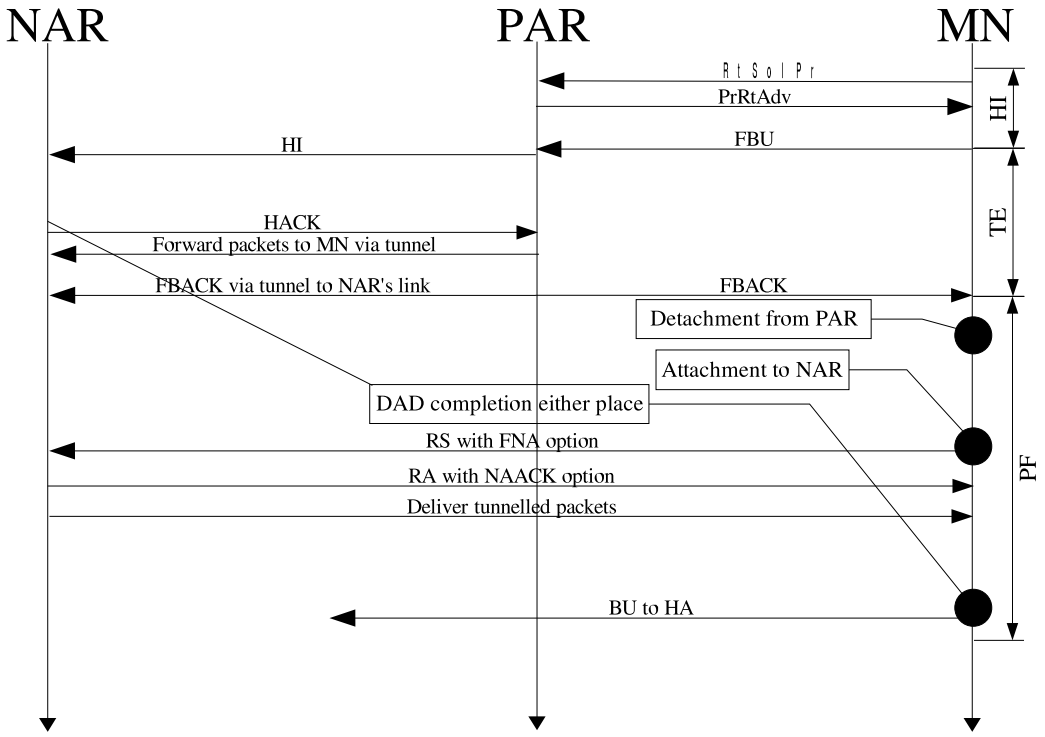


Figure 3.2: Anticipated Fast Handover operation

Handover initiation is usually initiated by the MN. The coverage area of the

two ARs have to overlap in order for anticipated fast handover to occur[1] (The non-anticipated case as supported by 802.11b access networks out of the box shall be discussed next). The MN knows that it should handover to NAR when it receives a L2 indication usually called an L2 trigger[2] due to perhaps waning received signal strength from PAR below some threshold level or other factors unrelated to link quality. The MN sends a Router Solicitation for Proxy (RtSolPr) to its current AR i.e. PAR with the link layer identifier of the prospective access point e.g. base station ID. This information is provided by the specific L2 technology. The PAR responds by sending a Proxy Router Advertisement (PrRtAdv) with the NAR's link layer address, its IP address and also any network prefixes to enable the MN to generate a suitable new care-of address (NCoA) on the new link. If the network is the one to initiate the handover then it will send an unsolicited PrRtAdv to the MN.

Tunnel establishment involves the MN sending a Fast Binding Update (FBU) some time after receiving the PrRtAdv[3]. Once PAR receives FBU, it will send a Handover Initiate (HI) to NAR. The purpose of HI is to establish a bidirectional tunnel between PAR and NAR to allow use of the previous care-of address (PCoA) on NAR's link as well as to validate whether the NCoA is valid and unique at NAR's link. When NAR receives HI it will set up a host route for MN's PCoA by creating a neighbour cache entry that points to PCoA with state of STALE i.e. address resolution required. NAR should also defend NCoA via proxy neighbour advertisement for a short period of time after verifying uniqueness of NCoA. NAR sends back a Handover Acknowledge (HACK) to PAR. PAR will subsequently send a Fast Binding Acknowledgement (FBACK) to MN. Upon receiving FBACK, the MN will know that it has permission to use NCoA on the new link.

Once the MN has arrived at the new link[4], it will send a Router Solicitation (RS)

[1] Otherwise there is a break in communications with the duration dependent on the size of the "gap" and how fast the MN is moving through this no coverage zone.

[2] L2 "source trigger" in this case [37] (revision 6)

[3] can even be after it has attached to the NAR too

[4] Layer 2 "link up" trigger can notify MN that it has attached to new link

to the AR on this link which should be NAR. Attached to this RS is a Fast Neighbour Advertisement (FNA) which is just an IPv6 address option with the NCoA inside it. The purpose of this is to notify the NAR to stop defending the NCoA if the NAR had previously set up a proxy neighbour cache entry. The FNA will also start the forwarding of packets addressed to PCoA to the MN on this new link by creating a neighbour cache entry at NAR that points to PCoA as been on-link and with state of REACHABLE i.e. address resolution not required. If the FBACK had indicated NCoA was acceptable then MN can start using that as source address after sending BU to HA and CNs. However if FBACK indicated that NCoA could not be verified by NAR for whatever reason then the Neighbour Advertisement Acknowledge (NAACK) option is included in NAR's Router Advertisement (RA) to again indicate if NCoA is valid or not. If both responses say that NCoA is invalid then normal address configuration process as described in Section 2.2.1.2 takes place. Nevertheless FMIP allows the MN to continue using PCoA for a short period of time[5] for ongoing communications with CNs until NCoA is acquired and thus a BU can be sent to the HA. I believe the description on the establishment of a host route in Sec. 4.2 and 4.3 of [37] can lead to incorrect behaviour due to the draft's ambiguity. If the HI and HACK exchange sets up a host route entry for the MN at the NAR, then if the normal path of packets goes through the NAR they will not be forwarded to the PAR anymore. While the draft does say that neighbour discovery i.e. address resolution should not be attempted until the MN's presence at NAR's link is known, this is only mentioned in one sentence in Sec. 4.2. Thus it is critical that FNA be sent by MN as soon as it arrives at NAR to reduce packet loss. Also there is a critical timing issue involved when setting up the tunnels because the MN has not actually arrived at the NAR yet and already the PAR can be tunnelling packets to NAR probably after receiving HACK from NAR. While the rest of the draft goes on to solve some of these timing issues by introducing L2 Triggers e.g. PAR can know at what point the MN detaches from PAR's subnet via

[5]BT_LIFETIME which is 2 seconds

a “link down” trigger, these add much more protocol complexity and couples each implementation of FMIP with specific L2 technologies. Even though a well defined software interface between layer 2 and layer 3 is described in the draft it remains to be seen whether this can be implemented without introducing some knowledge of specific L2 characteristics e.g. like determining which AR the MN will be moving to and providing that information to the MN. While this is outside the scope of the draft, it is nevertheless necessary for anticipated handovers to work.

I believe the non-anticipated case which was briefly described in the draft holds more promise for a simple and still effective mechanism at reducing packet loss and reducing handover latency without the coupling to specific L2 technologies required by the anticipated case discussed above. Non-anticipated fast handovers do not require knowledge of which AR will be the NAR. There is no exchange of PrRtAdv or RtSolPr at PAR’s link as shown in Figure 3.3. In fact the Handover Initiation phase does not occur at all. The MN upon attaching to new link (NAR’s link) as indicated by reception of a L2 “link up” trigger will send a RS with FNA. This is required to learn the default router’s i.e. NAR’s IP and link layer address. Then send a FBU to the PAR using its CoA (PCoA) as source address. The NAR if it supports FMIP has to allow in its ingress filtering rules any packets destined to PAR with a source address belonging to PAR’s subnet, in this case PCoA fulfils this criteria as it has been autoconfigured via the address configuration mechanism described in Section 2.2.1.2. Once FBU reaches PAR, the PAR will quickly do the HI and HACK exchange to complete the tunnel establishment stage. The NAR in my opinion should not need to verify the NCoA’s uniqueness nor defend it. In fact it should leave all NCoA configuration to the MN because there is now no advantage in having it done by NAR unless stateful address configuration is used. In the meantime the MN can use the PCoA as if it still existed on the old link as a bidirectional tunnel should have been established between PAR and NAR by then. Reception of a BACK from the PAR is confirmation of tunnel establishment. If we

take the view that the wireless link delay is much greater than the delay existing on the link between PAR and NAR then packet loss should be minimised. The MN is also free to simultaneously configure NCoA as done in MIPv6 as soon as it receives the RA that should include a NAACK indicating that NCoA is invalid to force MN to do address configuration as described in Section 2.2.1.2.

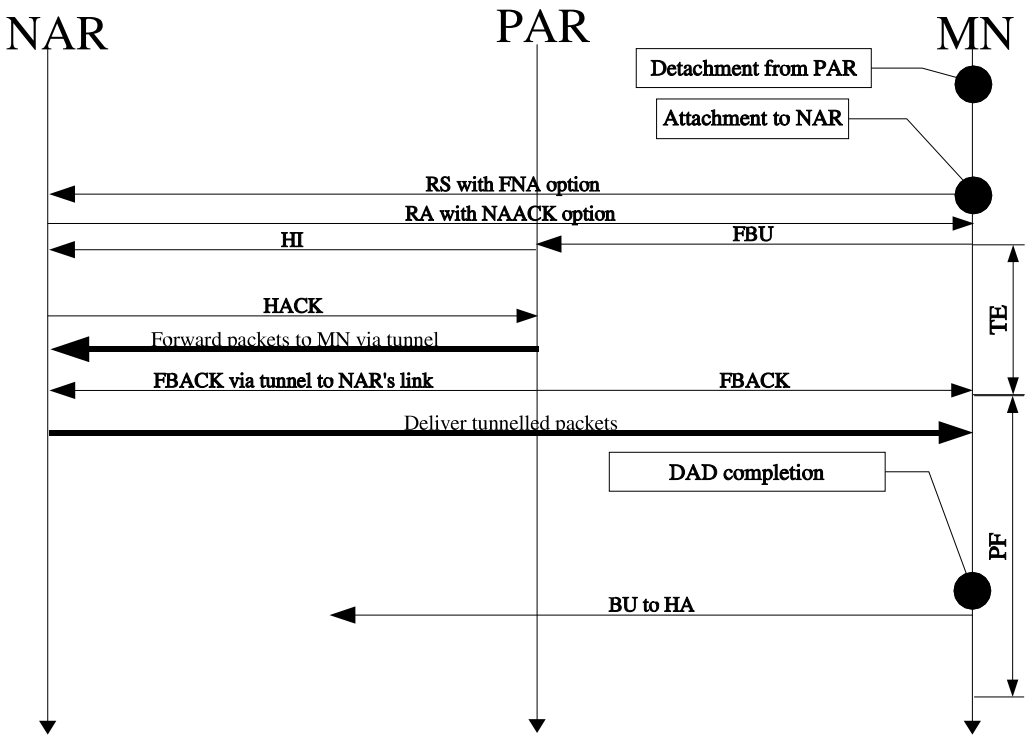


Figure 3.3: Non-anticipated Fast Handover Operation

The non-anticipated case while not able to reduce the rendezvous time to zero as the anticipated case promises to, it can reduce the overall handover latency as packets are forwarded quickly from the PAR to the NAR and allows the MN to resume communication via the PAR to NAR tunnel without waiting for registration with HA to complete as base MIPv6 would require. It buys the MN additional time to perform DAD and binding updates without interrupting communications.

3.2 Layer Two "Link Up" Trigger

In reactive handovers as mentioned at Chapter 3 there is a delay at the MN associated with recognising a new Layer 3 or Network Layer (L3) point of attachment called the rendezvous time. The previous section mentioned the use of the full complement of L2 triggers to implement FMIP. Since this would require some modification of existing L2 technology it would be a rather expensive exercise. The link up trigger (L2 Trigger) that is commonly implemented in virtually all wired and wireless devices is the "link up" trigger which from now on will simply be referred to as L2 Trigger.

This simple notification from L2 can help to reduce rendezvous time because it detects a change in the L2 link. Whilst it is possible that a L2 handover is not associated with an L3 handover this mis-prediction will have cost only a RS and the corresponding RA to tell the MN it had not changed L3 point of attachment and so should not initiate L3 handover. So the benefits for L2 Trigger should outweigh by far the cost except in situations where there are frequent L2 handovers or moving in and out of range of a solo coverage range so that large numbers of MNs performing router discovery could take up considerable bandwidth. This is not really too much of an issue in deployment because if the MN is residing at the periphery of the coverage range then the coverage range should be extended by adding extra APs or the MN has to restrict its mobility within the existing coverage range.

3.3 Fast Solicited Router Advertisements

During router discovery, when a mobile node sends a RS and awaits the RA from the local subnet router, there is a random amount of time[6] before the RA is sent back in response as specified in RFC 2461 [34]. This is so that Router Advertisements on the local subnet are desynchronised in cases where more than one router exists to prevent flooding of the network and collisions on common broadcast media like Ethernet.

[6] 0 to MAX_RA_DELAY_TIME (500ms default)

This is where an amendment to RFC2461 called Fast Router Advertisements[7] [38] can help. It is especially tailored for ARs that will have MNs visiting their links, as an expeditious solicited RA can reduce the rendezvous delay and hence the overall handover latency. This is achieved by choosing one router on the link to serve as the "fast RA" router. Only that designated router is allowed to respond immediately with a unicast RA to a mobile node that sends a RS with a proper[8] source address. There is an allowance for fast RAs up to a configurable maximum of FastRACounter that is 10 by default. Any more RSs beyond that will be scheduled for a normal unsolicited multicast RA as described in RFC 2461.

3.4 Optimistic Duplicate Address Detection

Optimistic DAD [39] is an Internet draft describing a method of allowing a node to use a tentative address i.e. an address undergoing DAD as source address which is contrary to the standard behaviour defined in [34]. It operates under the assumption that the addresses chosen for DAD on a particular link layer technology are well distributed so as to minimise the chance of duplicate addresses. This is certainly true of Ethernet based technologies such as IEEE 802.11b. Nodes implementing Optimistic Duplicate Address Detection (ODAD) will be able to resume communications much earlier after a handover by carrying out standard DAD in parallel.

ODAD enforces certain restrictions on what can be done with the tentative address so that disruption to the legitimate node who actually owns the tentative address will be minimal. This guarantee is enforced by the following:

- Router solicitations do not include a source link-layer address when sent from a tentative address. This ensures that the router will not associate the tentative address with the optimistic node and redirect any possible ongoing communi-

[7] Hereinafter referred to as Fast Solicited Router Advertisement (FSRA) in this thesis to avoid confusion with fast RA beacons which are unsolicited RAs.

[8] Any valid address besides the unspecified address.

cation sessions by the legitimate node to the optimistic node.

- The node forwards any packets to neighbours via the router. So only the router is aware of the node's presence on the link.

- Override flag is never set in neighbour advertisements. This will prevent the neighbouring nodes' neighbour cache entries of a legitimate node from been overwritten by the erroneous duplicate address of the optimistic node. This ensures ongoing communication sessions by the legitimate node with neighbours are never disturbed. This also allows the legitimate node to defend its address by sending a neigbhour advertisement (NA) with the override bit set to ensure the optimistic node knows that it has a duplicate address tentatively assigned and will stop using it.

There is also a procedure to generate a new random suffix and hence form another IP address to undergo DAD. This is a simple method to automatically recover from duplicate addresses since the standard behaviour in IPv6 calls for manual intervention.

3.5 Previous Care of Address Forwarding

Previous care-of address Forwarding was described in earlier revisions of the MIPv6 Internet draft[9]. It was removed due to security considerations[10]. Previous care-of address Forwarding (PCoAF) is the MIPv6 equivalent of smooth handover from MIP.

PCoAF uses only stock MIPv6 functionality. The MN regards the previous access link as its "home subnet" and sends a BU to PAR with the HoA set to the PCoA and the CoA to the NCoA as shown in Figure 3.4. Messages destined for the MN at PCoA will be intercepted, encapsulated and forwarded by PAR to the MN at its NCoA.

[9] see Section 11.6.6 of http://www.watersprings.org/pub/id/draft-ietf-mobileip-ipv6-18.txt

[10] basically a security association would need to exist between the PAR and the MN similar to the one that exists between the HA and the MN

PCoAF mitigates the effects of a topologically distant HA or CN by using the PAR to forward the packets addressed to the PCoA while the BU is sent to the HA and CN. This ensures a minimal number of lost packets when the traffic type is of the multimedia variety and the MN seldom acknowledges received packets i.e large synchronisation buffer so that the MN does not need to acknowledge packets during the handover in order to continue receiving packets.

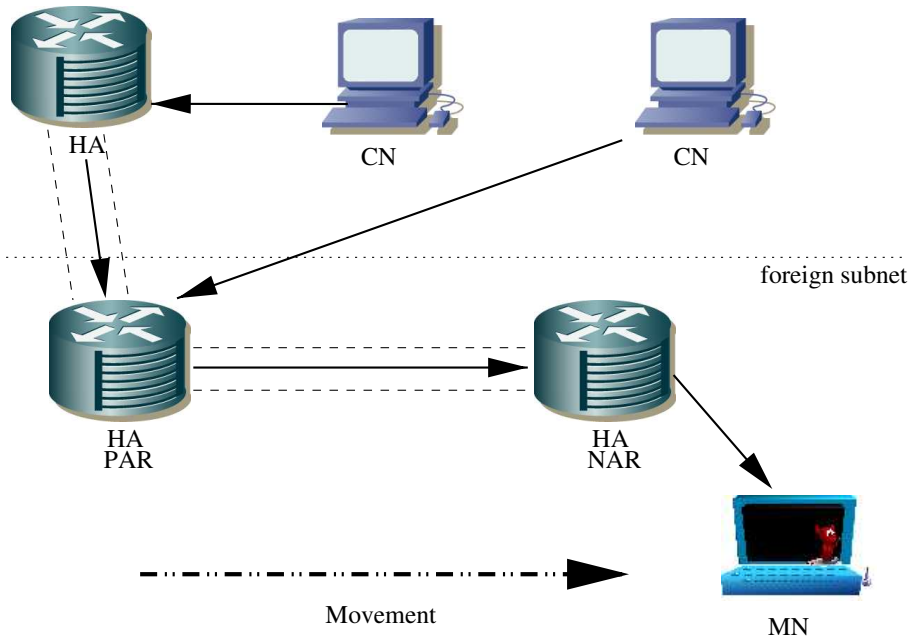


Figure 3.4: Previous care-of address Forwarding in action

This is also functionally similar to the non-anticipated fast handovers discussed previously at Section 3.1 in terms of been able to reduce the number of dropped packets after handover. Whilst non-anticipated fast handovers may have the upper hand by allowing the MN to resume communications using its PCoA as soon as it has detected movement to NAR and thus a greater reduction in the number of dropped packets, this comes at a cost of adding fast handover functionality at the edge of the network which is not a trivial task[11], and an additional overhead of signalling messages between PAR and NAR. All PCoAF requires is that all ARs have

[11]see [40] for the mathematical analysis of timing the tunnel establishment for optimal FMIP handover to prevent excessive overhead in signalling and buffering

HA functionality. However with the addition of ODAD, and Fast Solicited Router Advertisement (FSRA) this mechanism is at least as fast as non-anticipated fast handovers and can come close to the anticipated version. Close only because in anticipated mode of fast handovers the task of establishing a forwarding tunnel is accomplished just before handover whilst in the combined version of PCoAF there will still be some delay in configuring a CoA on new link and sending a BU to PCoA.

While these AR local extensions can improve handover times, they still can not solve the problem of excessive signalling that occurs when the MN moves frequently within a small geographical area while away from home. When the MN moves just beyond limit of link layer connectivity to its previous subnet, it needs to send a BU all the way to the HA even when it may be moving back soon into the previous cell's coverage range. MIPv6 was not designed with this in mind since its sole purpose was to allow Internet access on the move albeit not seamlessly and efficiently though. These shortcomings led to the development of localised mobility management protocols which are the subject of the next chapter.

Chapter 4

Localised Mobility Management

Wireless Internet is expected to surpass traditional methods of access[1] in the near future [41]. Table 4.1 depicts the general trend in the declining cost of wireless Internet access. Currently ubiquitous wireless Internet access via Wireless Local Area Network (WLAN) is not available yet due to the ten challenges identified by Ritter in [6]. One of them is fast handovers. MIPv6 handovers are subjected to variable delays as the signalling between the MN and the correspondent entities[2] introduce varying latencies that magnify the bursty 'packet-switched' nature of the Internet where network applications are already subjected to non-deterministic delays arising from congestion. Real time protocols demand stringent bounds on delay for packet delivery [41], otherwise noticeable degradation in quality occurs. As the MN moves over different provider networks as shown in Figure 4.1, it signals the HA and CN as a result of new points of attachment to the Internet. Eventually the round trip time of the BU and Binding Acknowledgement (BA) exchange will exceed the bounds on delay imposed by real time traffic and loss of quality is perceived by the end user. This effect is much more pronounced as the MN increases its mobility, triggering more handovers and causing more packet loss due to delayed delivery of packets to

[1] Ethernet, Digital Subscriber Line (DSL) and cable
[2] CN and HA

real-time applications[3].

Technology	**Data Rate(kbps)**	$/*kbps*
GPRS	53	$118.91
1xRTT	153	$25.42
Richochet	248	$2.43
WLAN	5500	$0.27
iBurst	1000	$0.25

Table 4.1: Cost (USD) of a standardised plan per available user bandwidth (in kbps) for different wireless access technologies. All data was from [6] except iBurst. IBurst estimate from Veritel at http://www.veritel.com.au/FreedomPricingandPlans.html assuming 12 months inc. purchase of card and not exceeding monthly download limit of 500MB

LMM[4] is the generic term for IP Mobility Management (MM) protocols that aim to minimise the excessive signalling (BUs) to its peers caused by frequent change of CoA. This is achieved by confining the mobility signalling within an administrative domain. A Localised Mobility Agent (LMA) is introduced into the visited domain in order to reduce the excessive round trip times that would otherwise result from registering with the HA. This is a relatively new research area as there have not been any large deployments of Mobile IP [8] and Mobile IPv6 is still in draft status.

The general mechanism of LMM can be seen in Figure 4.2 where an MN is initially moving away from its home domain into the visited domain. This is known as an *inter-domain* transition because the MN moves between different administrative regions. A home registration is sent to the HA and is classified as a *global mobility*

[3]these applications only accept packets that are within the bounds of delay as required by the audio and/or video codec and discard packets that do not satisfy this constraint

[4]micromobility is a subset of LMM generally denoting use over a small geographical area

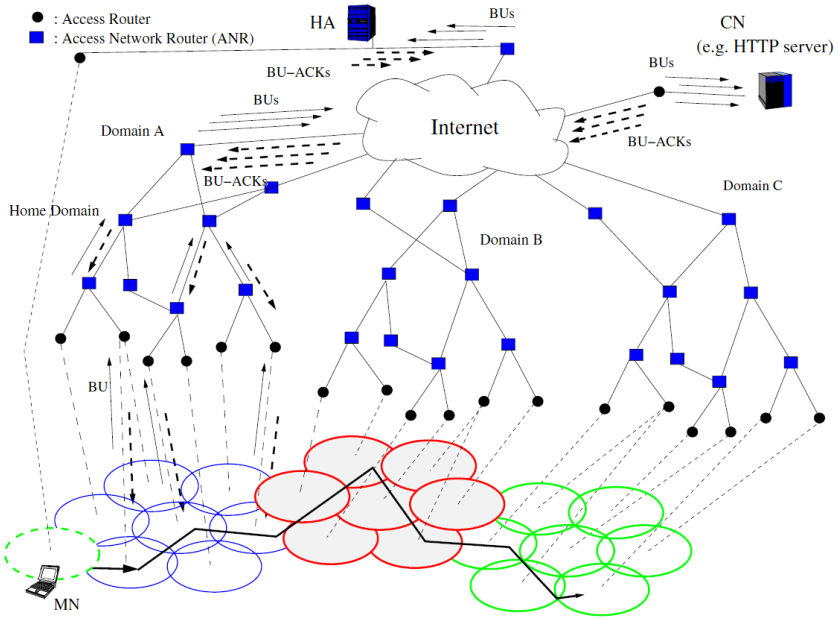


Figure 4.1: MN movement between networks in the global Internet requires mobility bindings to be updated with peers. (Reproduced from [41])

signal. Because the BUs are sent to the true peer entities (CNs and HA) and propagate across different administrative regions. This is the exactly the functionality that MIPv6 provides.

Inside the visited domain, the MN moves from one subnet to another and these are called *intra-domain transitions*. An intra-domain transition involves the exchange of *localised or regional mobility signals* with the LMA and so are confined within a single administrative region. This BU is also known as a Regional Binding Update (RBU). The LMA is thus responsible for maintaining a forwarding or look up table that maps the MN's *regional care-of address (RCoA)* known by the HA and potentially CNs from the global mobility signals sent by the MN, to the current location of the MN i.e. *local care-of address (LCoA)* within the visited domain that the regional mobility signals provide. In effect it is acting as a local HA within this foreign domain. LMM implies not changing the address the HA and CNs use to reach the MN for any host movement within the visited domain. By moving the MM to the LMA so that it is closer to the MN, the MM process is dictated by the

topological size of the administrative domain as opposed to the variable number of hops(represented as backbone round trip time in Figure 4.2) between the HA and MN across the wide expanse of the Internet. The indirection provided by the LMA is supported by empirical evidence from Kirby [42] that 68% of an MN's movement occurs within a local region. LMM alone does not guarantee the end-to-end delay constraints of real time traffic are satisfied. However I believe it is a prerequisite for reaching the goal of seamless mobility across the Internet.

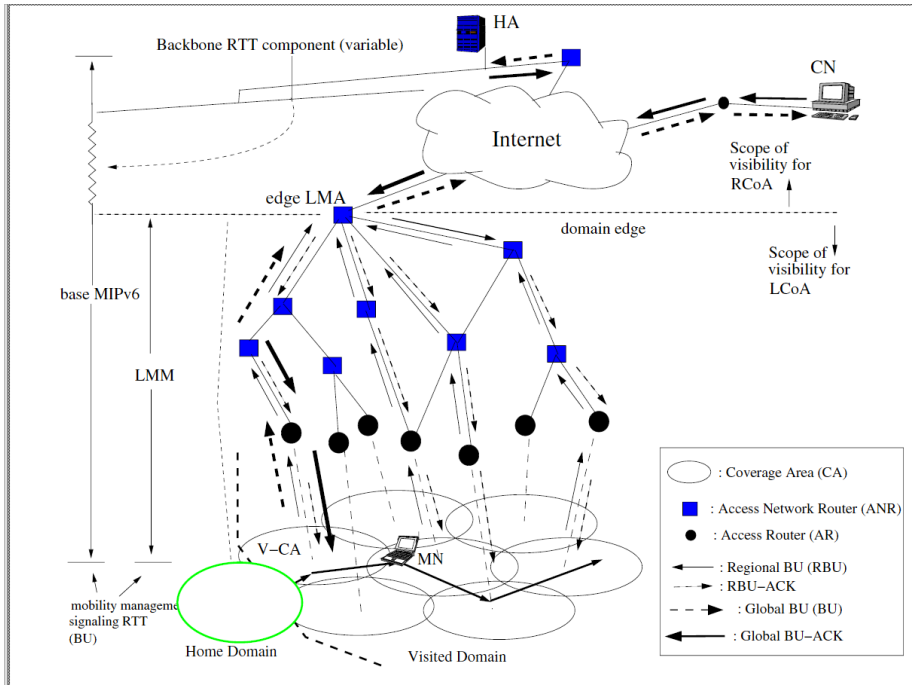


Figure 4.2: Introduction of LMA for MM reduces the number of mobility bindings to the HA when mobility is restricted to the foreign domain. (Reproduced from [41])

There have been attempts to extend MIPv6 or proposals of new MM protocols that can be used for both intra-domain as well as inter-domain mobility. However it makes sense to separate the two mobility functions due to the following benefits [43]:

- Allows independent evolution of LMM protocols and base IP mobility provided by MIPv6
- There is no difference between wired or wireless access networks to the core IP

network, because MIPv6 is the common mobility protocol used between access networks.

- Allows for different LMM solutions to cater for the different access network technologies
- Allows access network providers to use an LMM solution that suit their needs best [44]
- Does not prevent introduction of new protocols in the access network
- Confines intra-domain mobility signalling to access networks instead of dispersing throughout the core of the Internet on each L3 handover.

There have been many LMM proposals suggested in light of the fact that MIPv6 has not been deployed commercially yet. In order to evaluate these Pagtzis et. el. have formally submitted an IETF draft on *Local Mobility Management Requirements* earlier this year and elaborated on the requirements in [41]. The major requirements of interest are:

- robust so that no single points of failure or routing loops occur
- minimise the effect of triangular routing that is caused by introducing LMM
- no additional functionality required over base MIPv6
- incremental deployment
- no increase in signalling messages to HA and CNs over base MIPv6
- no increase in latency, packet loss, service disruption over base MIPv6
- LMM complexity scales at most linearly with size of domain and MN number
- Resilience to topological change
- minimal manual configuration

- no disruption to core IP routing outside of an administrative domain

Traditionally LMM protocols have been categorised as tunnelling or routing schemes [8, 44]. The routing schemes use conventional IP routing for redirection of the MN's CoA to its current location. The lookup tables are distributed amongst all mobility agents in the management domain. Examples of routing schemes are Handoff-Aware Wireless Access Internet Infrastructure (HAWAII) and Cellular IP. Tunnel-based schemes use LMAs for registration and tunnel packets to the MN with few agents having knowledge of the node's location. HMIPv6 and regional registration extension for MIP are examples of tunnel based schemes. Chiussi et. el. argue that routing based schemes such as Cellular IP have poor scaling properties as all nodes are required to establish forwarding tables to the MN on the up-link path and are not conducive to incremental deployment because all routers require this functionality.

Eardley et. el. disagree with this traditional classification as it does not in their view offer any useful information on the performance of the protocol [44]. In their view these protocols should be classified based on their scalability, in particular terminal scalability, throughput scalability and geographical scalability. They state that terminal scalability is the ability for many wireless devices (potentially in the millions) to be accessible in the one access network (AN) is really just a problem of addressing. Given a proper address allocation procedure they do not think this should be a problem. In their opinion this excludes auto configuration as the MN has no way of knowing which addresses are already in use. Geographic scalability is the ability to service small home networks all the way up to a global network and throughput scalability would require flexible network topologies with many access network gateways (ANG) as shown in Figure 4.3. Support for arbitrary topologies allows operators the freedom to deploy the network with the required resilience allowing multiple paths to avoid congestion. Multiple access network gateway (ANG)s are necessary for throughput scalability and robustness. They state that seamless

handovers[5] (handover management) does not need to be scalable. I disagree as the future of wireless Internet will most certainly be a multimedia rich experience so the signalling to local ARs to effect fast handovers will be crucial and dare I say all MNs will need this although perhaps not all the time and not altogether at once.

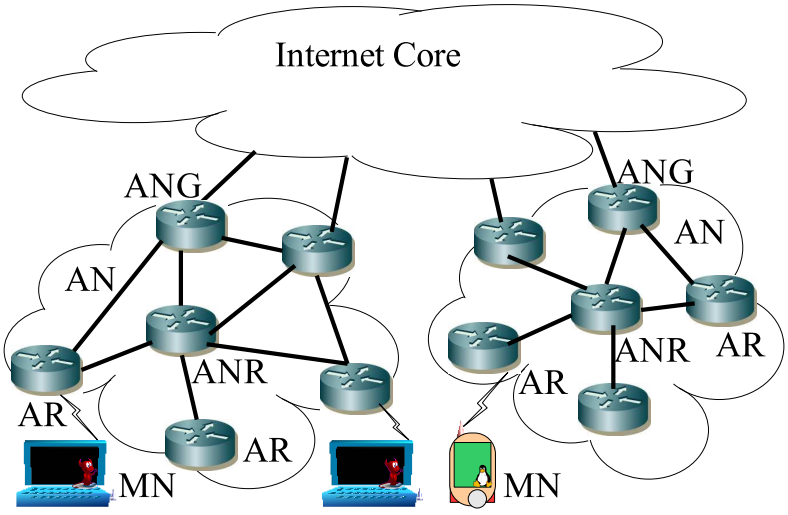


Figure 4.3: Conceptual AN architecture

They agree with Chiussi et. el. when it comes to criticising Cellular IP for been unscalable since the packets always travel the same path due to the strict hierarchy, so there is no provision for multiple ANGs. The surprising thing is that they also say that HMIPv6 if used in a hierarchical fashion will be no different from a performance point of view. The example used of mobile to mobile communication in the same access domain that can be very large, in the worst case may need to be established via the ANG is simply incorrect because in HMIPv6 route optimisation can be used to have the two nodes communicating directly rather than via the LMA if privacy is of no importance. So there should not be a need for a hierarchy of MAP registrations. This is also stated in the HMIPv6 draft [45, 20] too, where it is acknowledged a hierarchy of map bindings would degrade performance.

[5]minimising packet loss and delay

4.1 Hierarchical Mobile IPv6

HMIPv6 is simple in concept because it literally places the role of the HA into the LMA and referred to as a MAP [45]. The intra-domain transitions are defined as movements within the MAP domain. A MAP domain is delineated by the ARs that forward the same MAP option inside a router advertisement. The MN detects the presence of a MAP from the RA's MAP options. The MN chooses the best map according to its own policy[6] if there were more than one and perform global registrations for the first time only to the CNs and HA. While it continues to detect the same MAP option at every handover it will only need to send a regional update that is a BU to the MAP. If it does not detect the same MAP but another MAP is advertised it can bind with the new one. If no other MAPs are advertised then it reverts back to MIPv6. Either way whenever the MN leaves a MAP domain it will have to update the global mobility bindings.

The following is a list of advantages in deploying HMIPv6 as an LMM solution [45].

- Reduces the number of global registrations to the HA and CNs
- Actual reduction in number of messages over the wireless interface because only the MAP is updated with new mobility binding and not every CN for every MN transition within the MAP domain.
- Reduces handover latency because the return routability procedure of MIPv6 is required for every CN registration. As explained before this is at a minimum one and a half round trips. By binding to the MAP this eliminates the need to do CN registration.
- Only one binding update is required at the MAP before all traffic from CNs

[6] HMIPv6 draft recommends using a furthest MAP policy. This favours a mobile node that moves frequently so the number of bindings to the HA are reduced, since a further MAP's domain consists of more ARs. The down side is intra-domain handovers take longer.

and the HA are redirected to its new location.

- Those with privacy concerns can always use the RCoA as source address option when communicating with the CN so that route optimisation is on only at the global level[7], so the CN cannot track the movement of the MN within the MAP domain.

- Easy to deploy as no changes are required at the HA and the CNs

- Allows ingress filtering rules at ARs to remain unchanged in the MAP domain as the MAP supports reverse tunnelling from the MN. However this adds extra overhead.

While the advantages are numerous there are also many disadvantages. The major ones would have to be the non-optimal routing, MAP discovery mechanism and recovery from MAP failures and poor MAP selection algorithm. The non-optimal routing forces a single point of failure and so does not satisfy the geographic scalability requirement discussed in Chapter 4. The default MAP selection procedure will select the same MAP for all MNs at ARs that are the same distance from the farthest MAP which would be the MAPs at or close to the gateways of an administrative domain. Thus the MAP will be a bottleneck. The HMIPv6 draft notes that the use of the preference value may be able to control this to some degree, so for overloaded MAPs they decrease their preference value. However this will simply move the problem to another MAP and becomes the classic routing problem of flutter where the congestion hotspot just moves around. There needs to be a domain wide load balancing scheme so that the MAP boundaries for each MAP can be adjusted at the same time as their preference values and in coordination with other MAPs.

MAP discovery by default is a manual process because the MAPs and ARs have to be configured before deployment. The configuration involves enabling which interface in the MAP and/or AR should send or forward the MAP option on, and

[7] the truly paranoid can turn off route optimisation altogether by sacrificing efficiency

hence control the size of the MAP domain. For large administrative networks this involve a lot of manual work. While there exists an automatic method to propagate the boundaries of the MAP domain so routers know which interface to forward MAP options on [45, 17], the actual determination of the MAP boundary remains a manual process.

Can be very high in overhead with up to two sets of tunnel headers in both directions if the following conditions are met.

1. The MN cannot perform route optimisation with the CN since according to the HMIPv6 draft, MIPv6 does not mandate that all CNs be able to cache mobile bindings. So standard MIPv6 reverse tunnelling comes into play with tunnel entry point of RCoA and exit point of the HA's global address.

2. Alternatively the MN may not want the CN to even know its RCoA for privacy reasons and so the previous behaviour applies

3. Most ARs perform ingress filtering by default to prevent masquerade[8] so the MN will have to use reverse tunnelling with local care-of address (LCoA) as tunnel entry and the MAP's global address as tunnel exit. Either that or the network administrators will have to reconfigure all their ARs taking care to just allow the prefix for forming RCoA addresses through the ingress filtering rules. Thus reverse tunnelling is an advantage too, since it allows HMIPv6 to be deployed without configuration of AR ingress filtering rules.

There will always be one tunnel since the MAP has to keep the original packet intact and so a tunnel from the MAP to MN exists with tunnel entry of MAP's global address and exit point of MN's LCoA. While it is possible to eliminate even this tunnel by route optimising all the way to the MN, so the CN knows about the LCoA too, this defeats the purpose of HMIPv6. This mode of communication is only valid

[8]Malicious nodes can use any source address and a non-ingress filtering router will forward them even when they are not topologically correct

for very brief communication sessions where the MN is not likely to handover yet.

The MAP selection algorithm also needs to be much more adaptable than just a choose the farthest MAP algorithm. Further work has been proposed in this area and is presented in Section 4.3.

4.2 Fast Handovers in HMIPv6

Fast Handovers in HMIPv6 [46] aims to combine both HMIPv6 and FMIP to gain the benefit of HMIPv6's reduced signalling and registration times as well as shorter rendezvous time that FMIP buys. The argument goes that simply integrating the two protocols does not always reap the maximum benefit because:

1. increased tunnelling overhead
2. increased processing time at routers to process extra tunnel headers
3. the path that packets traverse may be such that the MAP is between the NAR and the PAR and the CN is closer to the NAR. Using this naive approach would mean that packets traverse an extra round trip back to the PAR for no reason at all

To overcome these problems they proposed to replace the PAR with MAP. They say that their solution cannot work with non anticipated fast handover. However I say that it is possible if you set up the ingress filtering rule at NAR with all the MAPs in the domain instead of just the neighbouring PARs. This requires more coordination but certainly not as much as when compared to the amount of L2 support and coordination between APs and ARs required by anticipated handovers.

4.3 Local Mobility Agent Selection Algorithms

For micromobility it is very important how the MAP is chosen as it determines the latency and frequency of inter-domain handovers. This in turn depends on the mobility of the MN. HMIPv6 allows nodes to select the MAPs themselves. This is a two edged sword, because on the one hand, the MN knows what its requirements are so it can select the best MAP from its perspective. On the other hand any global scheme that tries to enforce which set of MNs are served by which MAPs have a hard time of enforcing this, since the MN is allowed to register with any MAP. While the MAP is at liberty to reject any BUs, this trial and error process will take a while before the MN has bound with the "preferred" MAP especially when many MAPs are available for popular sites.

Hop-by-Hop-Based LMA selection proposed in [47] has better MAP discovery mechanism than HMIPv6 because it actually involves a form of pinging to discover the LMAs rather than requiring ARs to forward them. But it still finds the farthest MAP so assuming high mobility in visited domain just like HMIPv6. Their protocol satisfied all the LMM requirements [48] mentioned in [41]. The explanation of the recovery mechanism was rather brief no more than a sentence in each reference and was to the effect of using source routing to see if it can still get a probe response from the registered (furthest LMA). If it does not then it should use the stored responses to choose the next furthest to register with. If all that fails then restart probe discovery. This mechanism is slow if inter-domain transitions are frequent as it backtracks through the list of LMAs in previously visited domains. The RFC has expired as of June 2003 so perhaps the authors do not think it is worthwhile in pursuing further.

The same group has proposed another LMM solution called Mobile Controlled Movement Tracking LMA Selection [49, 50]. It is similar in strategy to the MPLS-based mobility [8] because it also selects a close (in terms of number of hops) LMA

to reduce signalling delay and yet far enough to cover the movement of the MN to reduce frequency of global handovers.

As mentioned before the rate of mobility is an important factor when deciding which MAP to register with. Kawano et. el. in [51] have taken this one step further and created a MAP selection algorithm that classifies the node's mobility based on its dwell time in a MAP domain and chooses a MAP to match[9] . In their performance evaluation of their proposed method for the network configuration as shown in Figure 4.4, there are only 2 types of nodes fast and slow. The threshold at which a MN is considered fast is 20km/h for their experiment. The MN does not choose the MAP but rather UA (User Agent) situated at the access router (AR) as shown in Figure 4.5. Whenever a node sends a BU it is the AR that intercepts this BU and the UA is instantiated to look at the Selection Table (ST).

The ST contains some simple entries that determine which MAP to register with for that particular speed profile. The ST's are most likely precomputed and placed in each AR in such a manner as to effect a distributed and equal load across all MAPs in the administrative domain. The AR then sends a BU to the corresponding MAP on behalf of the MN. The details of who the BU was originally addressed to and the mechanism of proxy BU requests are not stated in the article.

Their simulation experiment was conducted in a network with a hierarchy of an m-ary tree. i.e. 1x16x16x4 (The root or core router of the domain was connected to the sixteen MAPs designated simply as *higher* MAPs and each *higher* MAP had 16 MAPs below them designated as *lower* MAPs and each *lower* MAP had 4 ARs). The output parameters used to judge performance were the number of BUs and also the mean number of MNs managed per MAP. They compared their method against three schemes; one that always chose the higher MAP; one that always chose the lower MAP; a random MAP. Their method consistently performed better than the other three schemes where relevant and they also proved that their

[9]for details of the algorithm please consult [51]

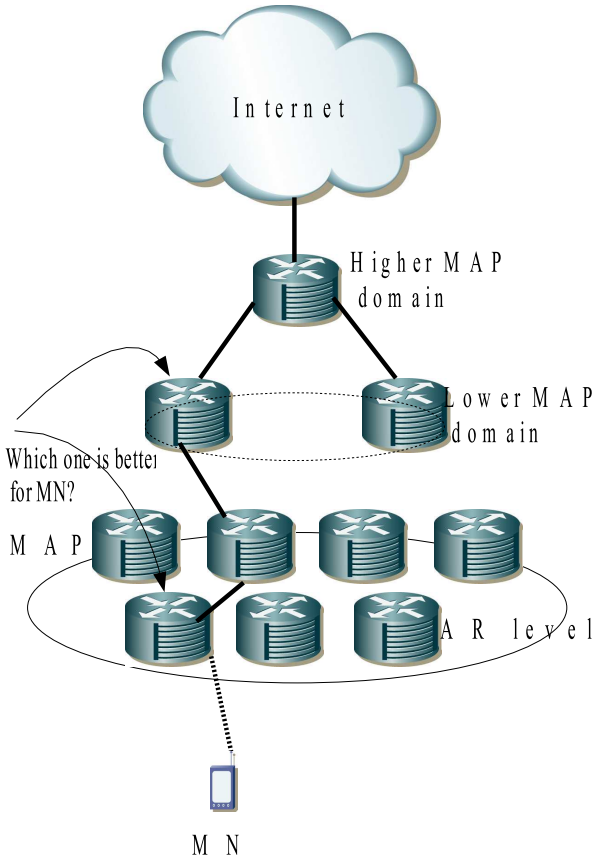


Figure 4.4: Typical network configuration for Kawano et. el.'s proposed method

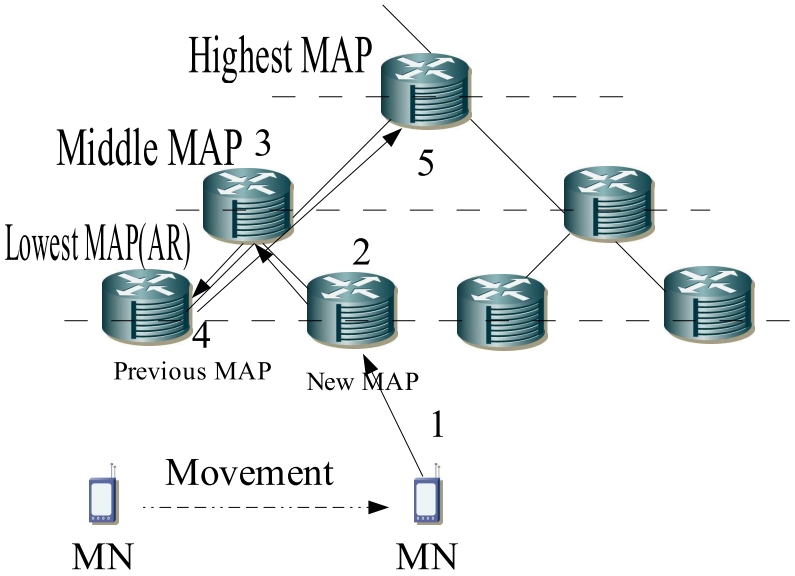


Figure 4.5: Kawano's mobility based map selection algorithm in action

protocol is independent of the network topology to some extent as they tried it on a different topology (1x4x16x16 m-ary tree) too. Most importantly they varied the actual threshold parameter from 0 to 50 km/hr in increments of 10 and were able to show that for threshold settings above 10km/hr their method also outperformed the other three. Thus the speed threshold need not be accurate just a reasonable enough estimate, since the algorithm is robust enough to tolerate a wide error margin. The only problems with these results are that they gave no mention of the simulation model used. The protocol at face value looks like it has some merit however there will usually be more than two levels of hierarchy in large 3G networks so it would be interesting to test if it could handle say up to six or seven hierarchies. Another difficult problem would be the creation and distribution of these ST tables as manually pre-computing them and distributing is not scalable for large access networks. The only feasible alternative is for extra signalling to be introduced to exchange the load information on each MAP and calculate the ST separately at each UA at regular intervals.

4.4 Other Micromobility Protocols

Cellular IP and HAWAII have both been mentioned previously. Cellular IP is a mechanism that modifies base IPv6 forwarding in such a way so as to allow upstream data packets sent by the MNs to create forwarding entries in the opposite direction. This in effect is very similar to the way Ethernet switches work. The MNs register the ANG's address as their CoA. The downstream packets which will be extracted by the ANG and have the HoA as source and flow through the modified routers and use these recorded routes in reverse to reach the MN's current location. Thus the whole access network becomes a flat host based routing scheme and so is not considered scalable by many.

Kim and Song in [52] suggest using a periodic binding update method to reduce

the number of unnecessary binding updates and hence reduce signalling load on network and processing delay for handover when a node is highly mobile[10] or moves back and forth frequently between a few links. Their method works by choosing a value for the configurable time period t based on the mobility of the node. At every t seconds the node will detect if the current network prefix as advertised by the router is different from its care of address. Only if it is different will it perform a layer 3 handover and send a binding update to the HA and CN. Otherwise it will reset the timer. The routers on the foreign links will have to be able to buffer the packets whilst the MN moves to different foreign link without notifying CN and HA. After MN registers new location with CN and/or HA then it is able to request previous foreign link to forward buffered packets to itself as shown in Figure 4.6. Their M/M/n queueing analysis found that as long as the probability of binding at every t seconds is less than 70% then there is an improvement in the processing delay as compared to plain MIPv6.

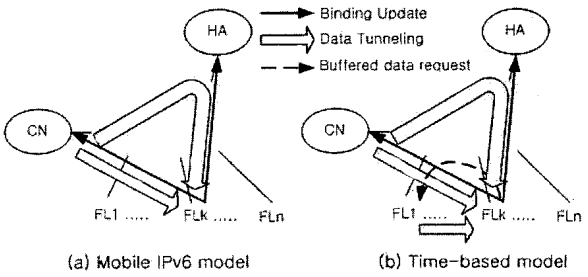


Figure 4.6: Time-based binding update in action

In [9] the authors claim that their proposed protocol Cellular Mobile IPv6 (CMIPv6) can reduce L3 handover by using foreign home agent (FHA)s[11] to track location of the MN that according to the authors is better than HMIPv6 for cellular networks. The FHA appears to spy on the link for BUs and will store some location information into a Location Table (LT). When the MN moves and sends a BU to its peers, the FHA is able to determine the NCoA of the MN from the BU that passes

[10] approx. 112km/hr in their analysis
[11] a modified router

through it to the peer node. Thus it is able to set a temporary forwarding from the PCoA to the NCoA for any packets in transit before the BU arrives at the MN's peers. This is similar to Cellular IP except this modifies normal packet processing during handover only. It does improve handover latency over MIPv6. CMIPv6 is most effective when the rendezvous time is small in comparison to registration time as communications resumes just after the BU is sent. Their evidence for this is that the Linux MIPv6 implementation takes only 200ms for acquiring a CoA. This is an exaggeration because it does not seem to take DAD into account, unless their link-layer technology does not require DAD.

There are also LMM schemes that borrow successful protocols from different domains such as Multi Protocol Label Switching (MPLS) from Traffic Engineering (TE) [8] and a multicast-based one called Multicast-based Micro Mobility [53]. Basically both of these protocols borrow from the signalling primitives already available and which have proven to be effective for their application areas. For MPLS the argument is that MPLS is actually more efficient than IP itself since MPLS labels are used for forwarding purposes. It should be more scalable since MPLS can handle thousands of labelled paths and has proved more than capable. For the multicast-based method their argument was that the multicast tree is perfect for forwarding to the MN's current location. The route will always be route optimised since that is a property of the multicast algorithm. It uses multicast group joins and leaves to notify the network of where the MN is exactly. Thus it is rather similar to Cellular IP in that the routing information is distributed in many nodes but this is much more efficient because the author has used some kind of algorithm to aggregate the state information so that it occupies less memory.

Chapter 5

Performance Evaluation of Mobile IPv6 Enhancements

5.1 IPv6Suite Simulation Framework

In order to carry out the performance evaluation of MIPv6 and its extensions, I have chosen to use simulation as the tool instead of mathematical analysis. Simulation is a valid tool for determining the performance of communication protocols especially when mathematical models are too complex [54] or intractable. Many of the communication protocols involved in large networks are very detailed and can give rise to complex behaviour i.e. extra retransmission of some protocols may increase overhead many times. We[1] have constructed an IPv6 simulation suite called IPv6Suite [55] released under the GPL[2]. IPv6Suite was initially based on IPSuite[3]. It is now significantly improved and adds the following protocols:

- RFC 2373 IP Version 6 Addressing Architecture [31]
- RFC 2460 Internet Protocol, Version 6 (IPv6) Specification [13]

[1] Eric Wu and I
[2] http://ctieware.eng.monash.edu.au/twiki/bin/view/Simulation/IPv6Suite
[3] IPSuite is an IPv4 network simulation suite [56]

- RFC 2461 Neighbour Discovery for IP Version 6 (IPv6) [34]
- RFC 2462 IPv6 Stateless Address Autoconfiguration [30]
- RFC 2463 Internet Control Message Protocol (ICMPv6) for the Internet Protocol Version 6 (IPv6) Specification [57]
- RFC 2472 IP Version 6 over PPP [58]
- RFC 2473 Generic Packet Tunneling in IPv6 [33]
- Mobility Support in IPv6 (MIPv6) revision 18[4]
- RFC 2464 Transmission of IPv6 Packets over Ethernet Networks
- RFC 2374 An IPv6 Aggregatable Global Unicast Address Format
- Hierarchical Mobile IPv6 Mobility Management (HMIPv6) revision 6 [45]
- Optimistic Duplicate Address Detection [39]
- Fast Solicited Router Advertisements revision 4 [38]

IPv6Suite is built on top of Objective Modular Network Testbed in C++ (OMNeT++). OMNeT++ [59, 60] is a discrete event simulation platform written using C++ [61]. Here are some of the features from OMNeT++ that I find compelling:

* Many models are available including IPSuite [56].
* Scalable compared to other simulation systems see Appendix A and B of [60].
* Unlimited[5] levels of granularity via the compound/simple module approach.
* Object oriented paradigm
* Well documented

[4]Without the Return Routability procedure
[5]restricted by the amount of computing resources at your disposal

* Author is very helpful and friendly

* Open Source and free for academic research

The goal of the IPv6Suite is to be as accurate as possible without sacrificing performance and scalability. It needed to be scalable because we plan to use IPv6Suite as a platform to simulate realistic and very large scale networks in order to understand how well new proposals such as MIPv6 perform when tested in network configurations larger than the size of laboratory testbeds. Please refer to our paper [62] where details of the modifications to OMNeT++ for parallel simulation on computing clusters are explained. A hands on tutorial for a basic parallel simulation is provided in [63]. For an introductory overview of IPv6Suite please refer to our paper [55]. For a detailed design of IPv6Suite please turn to Appendix A.

5.2 IPv6Suite Deviations from MIPv6 IETF draft

Eric Wu and I have implemented draft 15 of MIPv6 with some updates and clarifications from draft 18 too. However the major omission of draft 18 would be the missing return routability procedure that adds an extra round trip and a half. It is a prerequisite before sending bindings to CNs as explained in Section 2.2.2.2.

Neighbour Unreachability Detection is another method of detecting MN movement which is not implemented in our simulation. This is no loss because the Mobile IPv6 for Linux (MIPL) implementation does not use Neighbour Unreachability Detection (NUD) either [36] because NUD is one of the slower forms of movement detection mechanisms. NUD is started when a different network prefix is advertised by a new AR to ensure that the HA or PAR is not reachable on the local network anymore since it is possible for a link to have two ARs advertising different prefixes.

Our MIPv6 implementation undergoes DAD on the acquisition of a new CoA only. DAD is not done for the link local address upon visiting a foreign subnet as

RFC 2462 states that stateless autoconfigured link local addresses need to have DAD done once only. However the latest revision[6] of MIPv6 draft has stated that DAD SHOULD be done upon visiting a new foreign link[7]. Most simulations do not even consider the effect of DAD. A case in point is Figure 10 of [9] that shows a value of 200ms for acquiring a new CoA that is well below the requirement of awaiting DAD completion that should be at least RETRANS_TIMER[8] seconds.

MIPv6 stipulates that the first home registration to HA should wait for BA before signalling the CN. However in draft 24 there is also one sentence that reads as always wait for the BA from HA before sending BU to CN. I believe this interpretation to be correct because return routability depends on the registrations to the HA and CN occurring in sequential order. This is so that the HA knows the MN's current location (CoA) before return routability can succeed and hence a successful registration at the CN. In my MIPv6 model there is no delay before registering with the CN as that is done immediately after sending BU to HA. I do not see any problems with this because the packets sent by CN to MN in the route optimised mode of communication bypasses the HA. However return routability will not allow this optimisation so the simulation results are somewhat optimistic about the handover performance for all the mobility management protocols tested.

The HA should perform DAD on behalf of the MN for the HoA at the first binding. This is to ensure that no other node has acquired HoA during the window of opportunity available when the MN moves away from its home subnet and before the HA starts defending the HoA. This will introduce a significant delay during the first handoff only. ODAD cannot be used here since the purpose of a HoA is a permanent identifier like a phone number for the MN, generating another HoA is not acceptable. A foolproof solution to this is to use some form of stateful configuration like Dynamic Host Configuration Protocol for IPv6 (DHCPv6) at the home subnet

[6] 24 at the time of writing
[7] see **Section 3.4** of [39] for an explanation on why
[8] one by default

to ensure that the HoA is not assigned to another node even though the chances of autoconfiguring the same HoA are slim. This initial DAD on HoA by the HA is not done in the simulation because we can assume that if users want seamless handovers during the first handoff, they would have to use DHCPv6 or reduce the RETRANS_TIMER value or just turn off DAD[9] at the home subnet. The DAD approach is always a trade off between convenience and the chance that two nodes share the same address. DAD completion does not guarantee that the address is unique only the chance of a duplicate address has reduced. The default value for DAD is just one neighbour solicitation [30] and so on the lossy wireless links is prone to be lost.

In light of the extra delay caused by return routability that are missing from the simulation model, the simulation model is not an exact representation of the current state of the MIPv6 proposal at revision 24. These results are much more optimistic and the introduction of these delays would cause some forms of real time streaming that require stringent and very low delays to lose synchronisation during handover and render some of the more fragile voice and/or video codecs unusable or at least perform poorly when the MN transitions frequently.

5.3 Simulation Scenarios

Each simulation experiment is conducted with the input parameters set as stated in the text using the methods described in Appendix B.

The determination for the number of simulation runs (replications) for each experiment initially used Akaroa [64] to record the number of observations i.e. handovers to achieve a certain level of statistical confidence.However due to a technical problem, the observations were not recorded by the Akaroa library so a manual method was used instead. Based on the objective of 95% confidence level[10] and

[9] by setting host duplicate address retransmits variable to zero

[10] 95% of the time, conducting this experiment will produce confidence interval limits that bound

an approximate precision of $\pm 50ms$ I have determined that 100 runs were sufficient (assuming there were 4 handovers per run) based on preliminary trials. It is not possible a priori to establish the number of runs for a required confidence interval (CI) because the standard deviation σ is unknown as shown in Equation (5.1) [65].

$$n = \left(\frac{z_{a/2}\sigma}{E}\right)^2 = \left(\frac{1.96\sigma}{0.05}\right)^2 \tag{5.1}$$

All results have been tabulated with the number of handovers used and the calculation for the confidence interval limits for a 95% confidence level by Equation (5.2)

$$\overline{x} \pm \frac{z_{a/2}\sigma}{\sqrt{n}} \tag{5.2}$$

where $\overline{x}$ is the sample mean and $z_{a/2}$ for a normal distribution is approximately 1.96. The actual calculations used the Student-t distribution.

The links and their link delays in each scenario described below can be considered as an abstract and simplified version of the Internet with constant delay even though the simulation has modelled the path between the CN, the AR and the HA as a single link. The link delays in the scenario are are actually propagation delays in the simulation. However, they should be considered as a delay experienced by a packet travelling that path. This simple model should give results that are adequate in comparing the relative benefits of each scheme. For accurate depictions of the absolute handover latencies and packet loss, a large scale network topology representing the Internet is required at the expense of longer simulation times and complex modelling, development and configuration.

The output variables obtained from each experiment are the number of dropped packets per handover, the ping delay[11] and the handover latency. All experiments involve the *client* sending Internet Control Message Protocol (ICMP) ping requests

the interval where the population mean lies

[11] round trip time for the AR-local experiment and end-to-end delay for the others

to the *server* at a rate of 1 ping request every 50ms for the AR-local extensions experiment and 10ms for the PCoAF and HMIPv6 experiments. The length of the ICMP payload is fixed at 56 bytes.

handover latency This is measured according to the definition of L3 delay given at Chapter 3. Briefly it is the difference between t_1 and t_2, where t_1 is defined as the last time a data packet arrived at the MN before handover and t_2 is the time when the first data packet is received at the MN after handover.

packet loss per handover This is calculated from the difference in sequence numbers of the data packets i.e. $c_2 - c_1$, where c_1 can c_2 are the sequence numbers of the packets at times t_1 and t_2 respectively.

round trip time This is the time taken for a request packet to arrive at the receiver and a corresponding reply to be sent back to the sender. Replies that are not received or arrive out of order are ignored.

end to end delay This is the time taken for a request packet to arrive at the receiver. For the Regional Registration (RR) and PCoAF experiments end to end delay instead of round trip time was used to give a more accurate estimate for the handover latency.

5.3.1 Access Router Localised Handover Extensions

The AR-local handover extensions described in Chapter 3 can be evaluated using a typical factorial approach to determine how effective each one is individually as well as when combined. Figure 5.1 shows ODAD, FSRA and L2 as the factors under study on each axis and the origin represents the absence of each factor. This forms a unit cube with the eight corners each representing an experiment to explore every

[12]number of allowed consecutively missed router advertisements before triggering movement detection

Simulation Model	Parameter	Value
Mobility	MN_MoveSpeed	3ms^{-1}
IEEE 802.11	Bandwidth	1Mbps
	AP_BeaconPeriod∗	0.1s
	AP_AuthenticationWaitEntryTimeout∗	2s
	AP_AuthenticationEntryTimeout∗	2s
	AP_AssociationEntryTimeout∗	120s
	TxPower	0.1W
	ReceivingThresholdPower	0.0000073W
	HandoverThresholdPower	0.00001W
	ProbeChannelMinTimeout	0.01s
	ProbeChannelMaxTimeout	0.035s
	AuthenticationTimeout	2s
	AssociationTimeout	2s
	Retry	7
	ChannelsNotToScan	0
IPv6	LinkMTU	1280 octets
	DupAddrDetectTransmits	1
	RetransTimer	1000ms
MIPv6	MIPv6MaxRtrAdvInterval†	1.5s
	MIPv6MinRtrAdvInterval†	1s
	MaxConsecMissedRtrAdv[12]	1

∗parameters configured for access point only
† parameters configured for router only

Table 5.1: Common simulation parameters

possible combination. Each scheme can be turned on or off individually at compile time and does not require any extra settings[13] to be made.

The topology shown in Figure 5.2 is used to evaluate the local AR improvement schemes because it is the simplest topology for L3 handover.

The system variables have been set to the values shown at Table 5.1. Other host and router variables are left at the defaults as specified in IPv6 RFC 2461 and RFC 2460, and MIPv6 draft. These defaults are specified in the Document Type

[13]FSra is turned on at compile time like the other two but also requires a non-zero value in MaxFastRACounter variable to activate

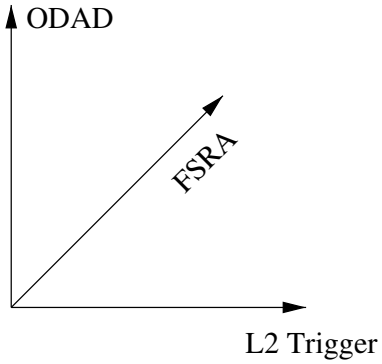


Figure 5.1: AR-local extensions as factors in experiment

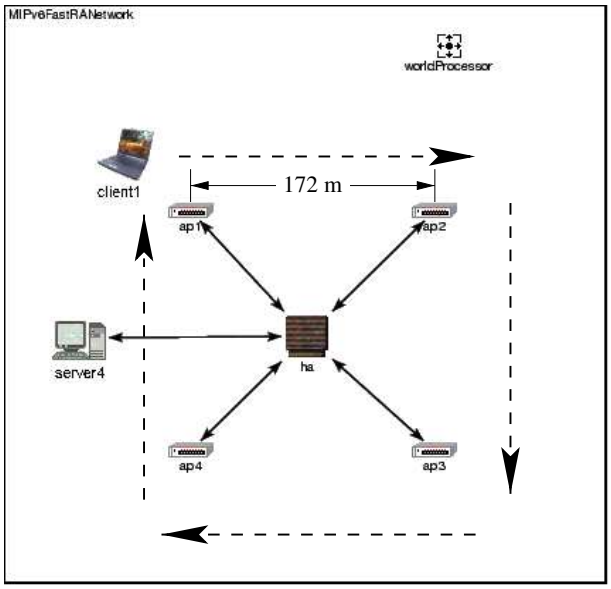


Figure 5.2: Handover scenario used in assessing AR-local extensions

Definition (DTD) of the IPv6Suite eXtensible Markup Language (XML) simulation configuration file as shown in Appendix B.

Another experiment with Fast RA beacons was conducted to study the effects of reducing the unsolicited RA interval on the handover performance and comparing it to the AR-local schemes. The variables are set to the values shown in Table 5.2. These are the absolute minimum permissible under the MIPv6 draft.

Parameter	Value
MaxRtrAdvInterval	70ms
MinRtrAdvInterval	50ms

Table 5.2: Parameters for Mobile IPv6 with Fast RA Beacons

5.3.2 Previous Care of Address Forwarding

Simulation scenario is shown in Figure 5.3. The wired link delays from the router to both HA and CN (server in Figure 5.3) are varied between 10ms, 50ms, 100ms, and 500ms to simulate different MN distances from the HA and CN or different levels of network load. The AR to AP link delays are at 1.5μ s. The configuration of the ICMP ping traffic was modified so that the *server* sends the ping requests and at a reduced interval of 1ms. The ICMP layer in the client is configured not to respond to the ping requests and only records the arrival of the ICMP ping requests. This recoding of the end-to-end delay differs from the ping delay which is a round trip time recorded in the experiment for the AR local schemes at Section 5.3.1. These changes are required to show the benefits of PCoAF and closely resembles the typical scenario of mobile hosts receiving real time multimedia streams from a server.

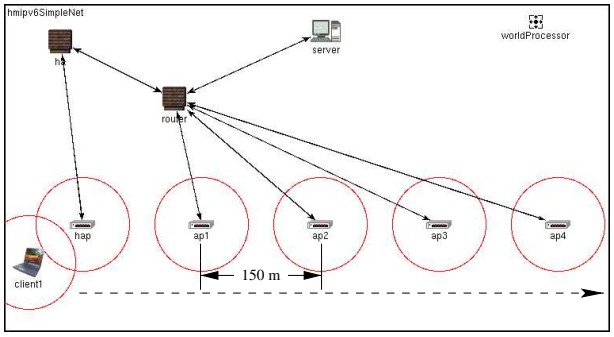


Figure 5.3: Simulation scenario with separated router and HA entities.

5.3.3 Hierarchical Mobile IPv6

Figure 5.4 is used to examine the performance of HMIPv6 along with permutations of the other handover schemes examined thus far. It is similar to the network topology

in Section 5.3.2 except a MAP is placed above the AR. While this is not the simplest HMIPv6 network topology[14] it is a more accurate depiction of how RR would be used in real networks. By varying the link delay between the MAP and AR we can simulate a hierarchical MAP topology where the link delay determines the level of MAPs at which the MNs are coerced to bind with.

The three schemes to be examined are HMIPv6, PCoAF and AR local improvements. This gives a total of 8 permutations. HMIPv6 is simulated by itself initially to determine the improvement in handover latency as that is one of the promised advantages of HMIPv6. Then add in the AR local improvements and finally add in PCoA forwarding too and see if there is significant improvement.

For each of these eight permutations the propagation delay labelled $d_{Internet}$ for the link between the MAP and the CN/HA, and d_{MAP} for the link between the AR and the MAP was varied. $d_{Internet}$ represents the general delay through the Internet for packets travelling between the MAP and HA/CN whilst d_{MAP} represents the size of the MAP domain or as mentioned previously at which layer the MN wishes to bind with in a "virtual" hierarchy of MAPs. The values for $d_{Internet}$ are 0.05s, 0.1s, 0.2s and 0.5s. This represents the distance that the MN travels from its home subnet. t_{MAP} is set to 0.002s or 0.02s which represent a MAP at the AR and a small MAP domain (or low MAP in the MAP hierarchy) respectively.

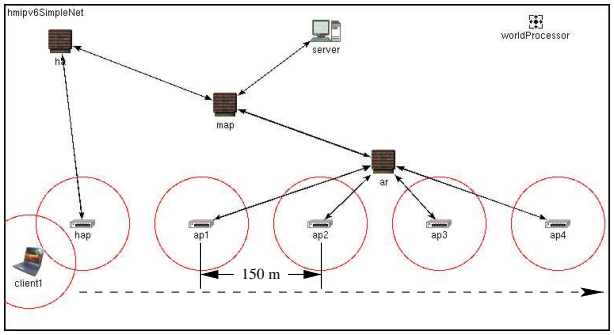


Figure 5.4: Simulation scenario for HMIPv6

[14]the simplest would just be to merge the MAP and AR into one network entity

Chapter 6

Discussion of Results

6.1 Access Router Localised Handover Extensions

The results for handover latency and packet loss are in Table 6.1 and Table 6.2 respectively. I have not separated the results for the different types of handover scenarios i.e. home-link to foreign-link, foreign-link to foreign-link and foreign-link to home-link as the authors in [66] have done. The reason is that I wanted to find out the overall performance of the protocol regardless of the type of handover. MIPv6 in real use would not have a fixed and predictable pattern of mobility. As the movement from and to home subnet occurs only once there are twice as many handovers among foreign subnets and only one of each remaining type. I have removed data from some of these different handover types when the analysis requires this as stated in the text.

The number of observations for ODAD, MIPv6 and FSRA are relatively less in comparison to the other handover schemes because the others were repeated twice on another computer using the same random seeds. Each repetition was done when many defects in the simulation model were removed. The relative performance for the above mentioned three schemes with deficient runs were already apparent and also limited time prevented me from repeating the experiment to reduce the number of "bad" runs. A run is classified as bad when it does not finish. The handover values

are collected and run through a filter to ensure any suspicious values i.e. greater than an impossible threshold were removed. The other handover values in the same simulation run were unaffected. As the stability of the simulation improved the number of samples removed reduced to zero in later experiments.

To ascertain the accuracy of the results a few comparisons were made with live wireless networks. Even with the reduced result set of MIPv6 the mean MIPv6 handover latency of 2.61s compares favourably to an experimental result obtained from a real world test bed of 2.54s for a single MN scenario [35, 42]. This lends credibility to our simulation model.

	No. of Handovers	Mean	Lower CI limit	Upper CI limit
l2trig-odad-fsra	400	3.55e−01	3.42e−01	3.67e−01
l2trig-odad	396	5.67e−01	5.47e−01	5.86e−01
fast-beacons	209	1.13e+00	1.07e+00	1.19e+00
l2trig-fsra	400	1.22e+00	1.16e+00	1.28e+00
l2trig	400	1.43e+00	1.37e+00	1.49e+00
odad-fsra	399	2.42e+00	2.38e+00	2.46e+00
odad	398	2.50e+00	2.45e+00	2.54e+00
fsra	344	2.54e+00	2.49e+00	2.58e+00
mipv6	333	2.61e+00	2.57e+00	2.65e+00

Table 6.1: Mean and CI of handover latency for AR-local extensions

	No. of Handovers	Mean	Lower CI limit	Upper CI limit
l2trig-odad-fsra	400	5	5	5
l2trig-odad	396	10	9	10
fast-beacons	209	21	20	22
l2trig-fsra	400	23	22	24
l2trig	400	27	26	28
odad-fsra	399	47	46	47
odad	398	48	47	49
fsra	344	49	48	50
mipv6	333	50	50	51

Table 6.2: Mean and CI of packet loss for AR-local extensions

The round trip time plot in Figure 6.1 is typical of all the AR-local extensions as shown in Figure 6.2 where only FSRA, MIPv6 and all AR-local extensions combined are shown. They all have a long right tail which is a characteristic of the random exponential backoff in the IEEE 802.11b media access control protocol. In this simple simulation scenario of only a single MN as opposed to the randomness encountered in the real world, there is no difference in the round trip time.

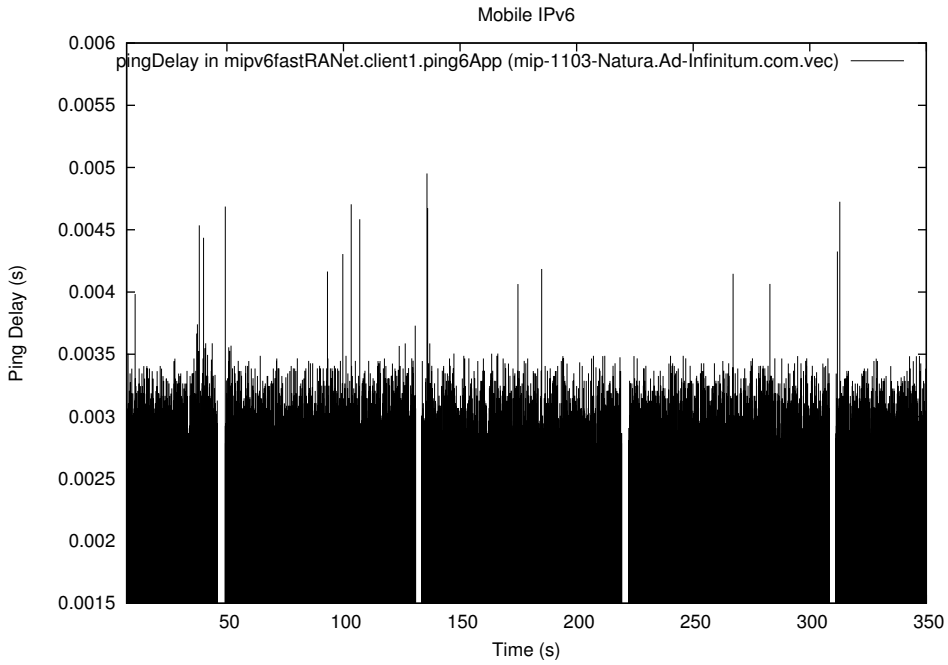


Figure 6.1: Time series plot of round trip time for a single random run of MIPv6

For the returning home case, the handover is assisted by the fact that the MN already has HoA acquired and so is faster than the other types of handover. The longest handover is typically the one that occurs when moving away from home. The reason for this is that the MN is supposed to wait for a BA from HA, to ensure that the HA has tested by using DAD procedure the HoA for uniqueness as the HoA may have been assigned to another node while the MN was moving away from home. While the probability for this scenario is not likely due to the uniqueness property of the interface identifiers it is nevertheless a requirement in the MIPv6 draft [16].

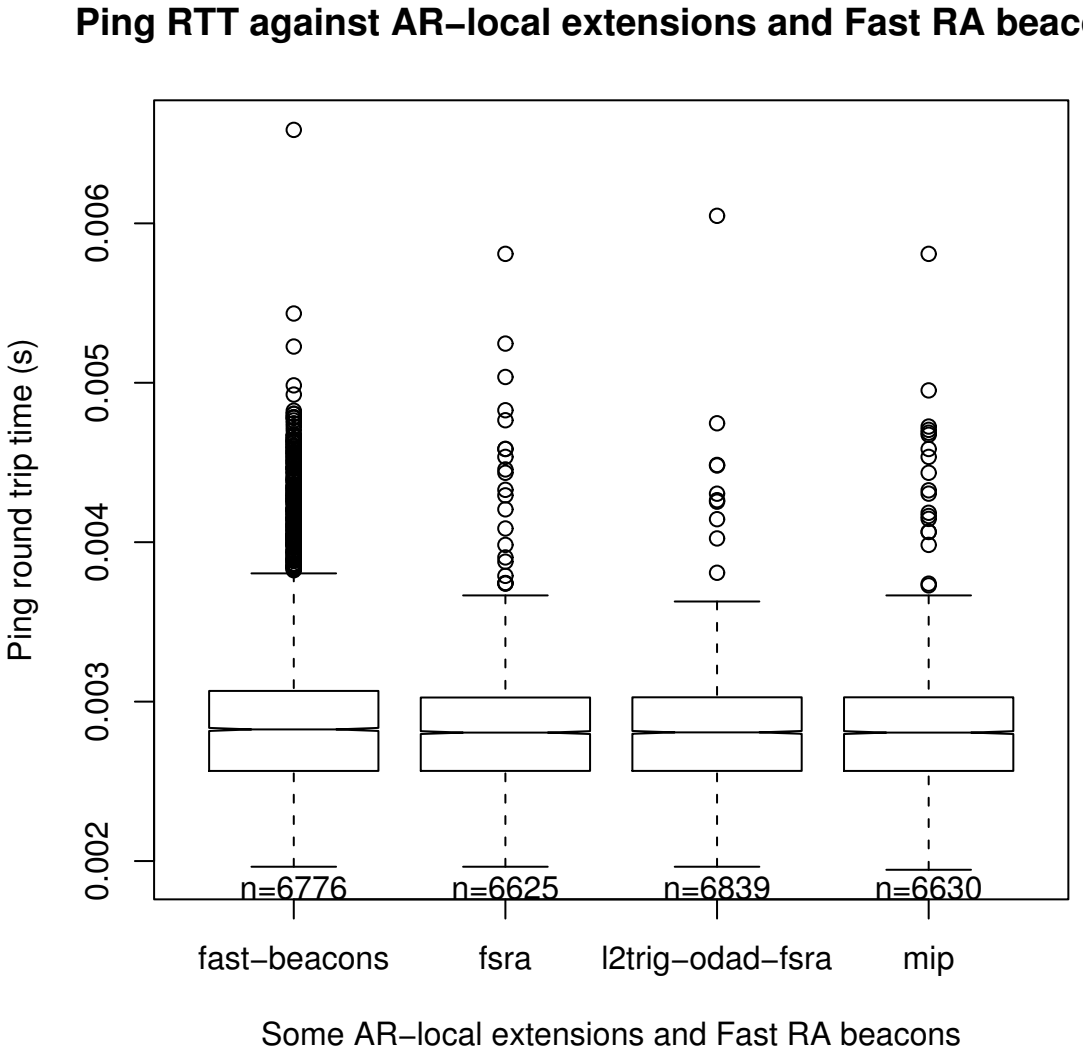


Figure 6.2: Box plot of ICMP ping round trip time for selected schemes in AR-local handover extensions experiment

Referring to Figure 6.3[1] it is clear that when all three AR-local extensions are used together will result in the fastest handovers. Notice however that for the cases when L2 Trigger is used, the handover latency can at times be as good as all three techniques combined together as shown by the outliers in the plot. This is not possible because only ODAD can reduce the handover latency below 1 second

[1]Most plots were produced with the help of R [67, 68]. For more information on box plot interpretation please see Appendix C.

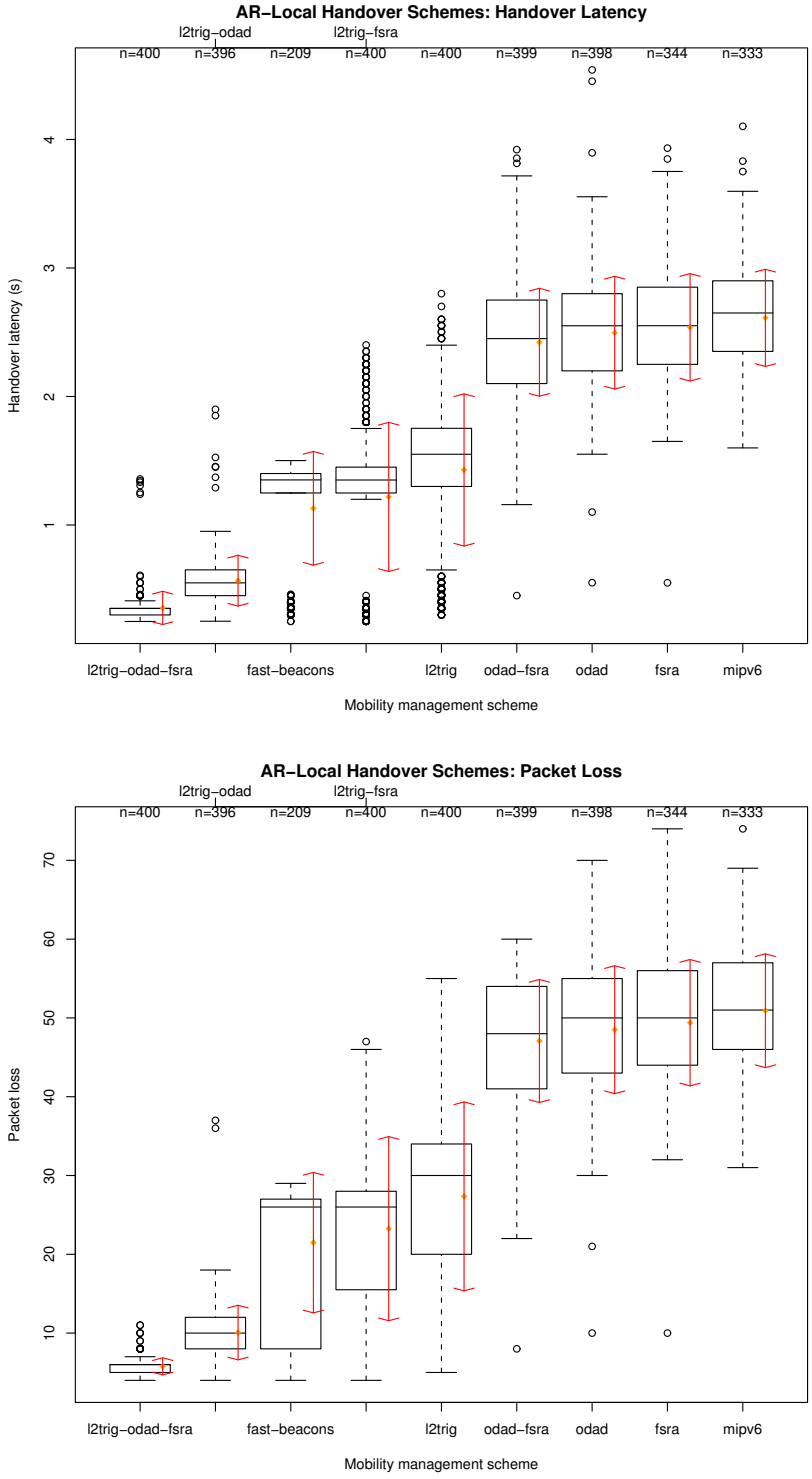


Figure 6.3: Box plot of handover latency (top) and packet loss (bottom) for the various combinations of AR-local extensions and fast RA beacons

as acquiring a new CoA uses DAD. This is attributed to the fact that Figure 6.3 includes the results from the 4th handover when the MN returns home and so does not do DAD. The same plots without the 4th handover are shown at Figure 6.4. There is a clear linear relationship between the handover latency and packet loss[2], because the traffic is at a constant bit-rate and there are no errors on the link layer and also the buffers in the routers are infinite.

6.1.1 Round Trip Time Irregularities

In Figure 6.1 there appear to be some large spikes in round trip time just after handover. This is due to the neighbour discovery of the PAR[3] failing as some ping packets were awaiting address resolution at the crossover boundary and have reselected the old router.

This happens because the missed RA movement detection method will set the neighbour entry of PAR to stale and since the pings occur so rapidly they will occur before the MN has had a chance to send RS and receive an RA from new AR. Meanwhile more packets will be queued awaiting the outcome of this address resolution. As neighbour discovery retries a few times separated by RetransTimer (one second) this happens exactly one second after too so it interferes with the AR sending back ping replies. This information was garnered from the debug log file generated with Libcwd [70]. See Section B.2 for further information on the use of Libcwd. The spikes are a direct result of the 802.11 back off mechanism that kicks in when media contention occurs.

There appear to be some smaller random spikes that show up in between handovers too. These are due to collisions caused by the MN sending ping packets on regular basis and the AR's Router Advertisement spaced at random intervals apart. While the chances of these two things colliding are few when the mean RA interval

[2]Only L2 Trigger combinations and Fast RA beacon do not follow this rule when considering the returning home case too when comparing the plots in Figure 6.3.

[3]The router's previous interface in the simulation scenario.

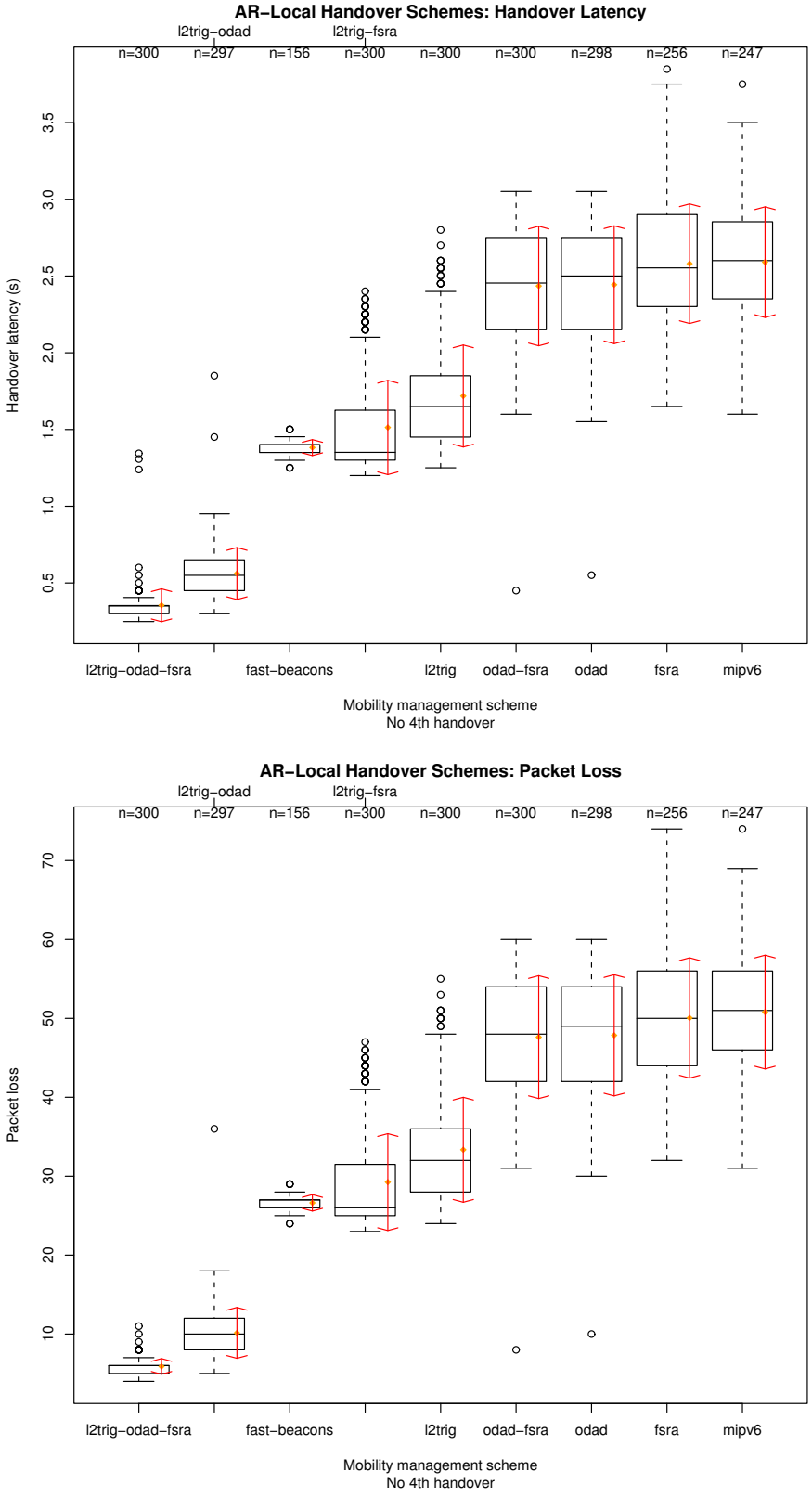


Figure 6.4: Same plot as Figure 6.3 except the 4th handover i.e. the returning home case is omitted

is 1.25s the default for MIPv6, the fact that there are over 6400 ping packets sent over the lifetime of the simulation run of 250s then there will definitely be some contention for the shared wireless medium. In Figure 6.5 where the mean RA interval is reduced to over 16 times a second the collisions are much more frequent.

6.1.2 Optimistic Duplicate Address Detection

ODAD on its own offers a 110ms improvement in handover latency compared to MIPv6 as determined from Table 6.1. We would expect greater improvement given the faster CoA formation by removing the time taken to do DAD which takes one second by default. ODAD is used whenever a new prefix is advertised by the router so the meagre improvement is due to another random source of delay that is greater in magnitude than the constant delay from DAD and it is the rendezvous delay discussed at Chapter 3. When the MN moves to a new subnet physically, the MN is not aware of this until the missed RA movement detection mechanism has triggered. The missed movement detection triggers when two consecutive RAs are missed. This means that 2*MaxAdvRtrInterval which is 3 seconds by default will have to elapse without receiving a RA before the MN is aware that it has moved away from its prior location. This is sufficient time for the non-ODAD MNs to receive a RA from the new AR and finish DAD before the missed RA movement detection mechanism triggers. Figure 6.3 shows that ODAD is spread in a similar manner as MIPv6 confirming this analysis.

I believe further simulations with a modified value of the allowed consecutive misses of RA set to zero i.e. as soon as one RA is not received within the expected time interval, will have a notable impact on the effectiveness of ODAD, achieving even better handover than this study reveals.

6.1.3 Fast Solicited Router Advertisements

Referring to Table 6.1, there is a 70ms improvement for mean handover latency for FSRA from MIPv6. In [71] the improvement for just pure L3 handover latency without the L2 component was by a factor of 9.23. However they did not take DAD into account. In absolute terms, their improvement was 234.37ms, and is similar to my result of 190ms improvement over MIPv6 obtained from the combination of ODAD and FSRA (MIPv6-FSRA in Table 6.1). This is another independent validation for the accuracy of the MIPv6 simulation model.

The 70ms improvement in handover latency for FSRA is small compared to the theoretical reduction of 250ms due to the solicited RA delay in MIPv6. FSRA works only when the MN sends a RS. A RS is sent by the MN when it detects movement to a different subnet. The small improvement is due to the fact that the sending of the RS is random since the missed RA movement detection mechanism depends on the random unsolicited RA interval. For the combination of FSRA and ODAD (odad-fsra in Table 6.1) there is also a slight improvement of 120ms only over FSRA by itself. These two comparisons point to the detection of movement to the new subnet as the "catalyst" to reducing rendezvous delay. FSRA is of use only when the wireless link delay is less than the half of the unsolicited RA interval, otherwise it is useless overhead and you may as well wait for the unsolicited RA.

6.1.4 Fast RA Beacons

Looking at the handover latency and packet loss of Figure 6.3, it is clear that a reduced unsolicited RA interval[4] has better performance when compared to other extensions on their own. This is because the MN's Layer 3 or Network Layer is able to detect a transition to a new subnet quickly, within 60ms on average[5] from the arrival of the unsolicited RA.

[4] fast-beacons in all figures and tables

[5] Average of MaxRtrAdvInterval of 70ms and MinRtrAdvInterval of 50ms.

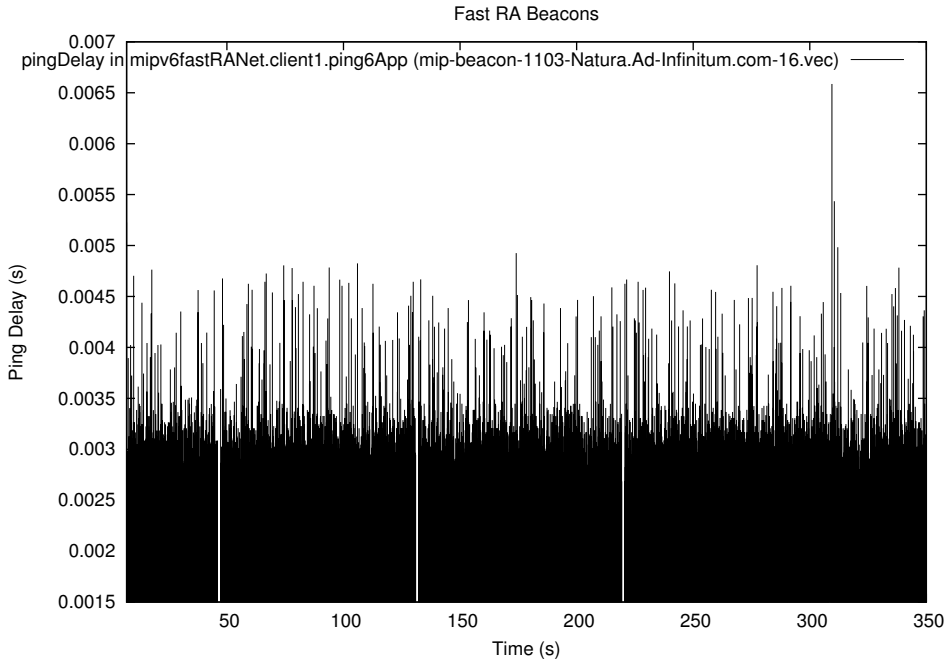


Figure 6.5: Time series plot of round trip time for a single random run of MIPv6 with Fast RA beacons.

Figure 6.2 is a comparison of ping delay[6] for fast RA beacons to base MIPv6, FSRA and the combination of AR-local extensions. Note the slight increase in the median ping delay which is not statistically significant at the 95% since the notches in the box plots overlap, and the heavier right tail. Where before there were a few random spikes as shown in Figure 6.1, when the normal RA advertising interval of 1.5s–1s was reduced to 0.07s–0.05s the spikes have become much more frequent in comparison as shown in Figure 6.5. This increase is by a factor of 14.25 for ping delays exceeding the cutoff point of 0.0036 seconds. The cutoff point was determined from the histograms in Figure 6.6. This is attributed to the RAs colliding with the ping requests, responses and to a lesser extent the neighbour discovery packets. The chance of collision has increased because RA frequency has increased[7],

The increased number of collisions on the shared wireless medium has a visible

[6]round trip time

[7]Ping packets are sent 20 times a second in a uniform manner. On average there are 16.67 RAs per second for the Fast RA beacon configuration under test as compared to MIPv6 which has only 0.8 RAs per second

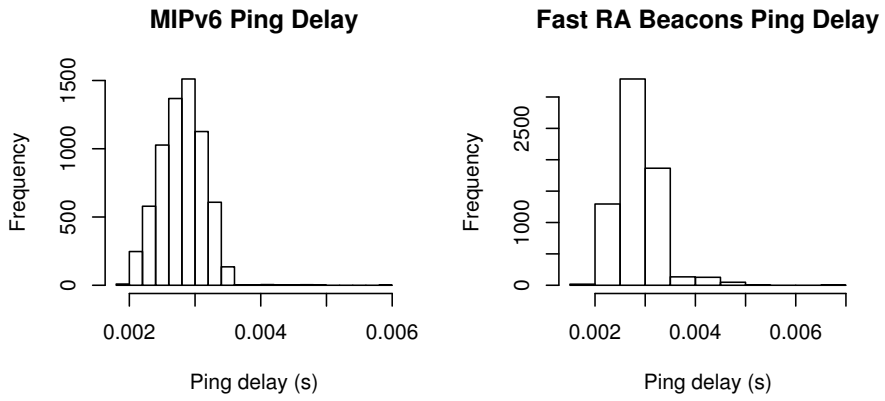


Figure 6.6: Histograms of ping round trip time for MIPv6 and Fast RA

effect on the jitter of ping packet arrivals as shown in Figure 6.7. Real-time audio and video traffic has bounds on jitter too [72].

The latest draft of MIPv6[8] specifies minimums for MinRtrAdvInterval and MaxRtrAdvInterval of 0.03 and 0.07 seconds respectively. This equates to an average of 20 RAs per second. That's up to an average of 20 extra times that other traffic on the network may have to resolve access to the shared medium.

Fast RA beacon is not reliable in popular sites because it does not scale to many mobile nodes with communication sessions in progress since the chance of collisions will increase.

6.1.5 L2 Trigger

The performance of L2 Trigger as shown in Figure 6.3[9] is different from base MIPv6 and the ODAD and FSRA extensions, in terms of the significant difference in the medians, smaller Inter-Quartile Range (IQR) and reduced whisker length. By actively detecting a change in L2 connectivity and sending a RS in response, the MN is able to reduce the handover latency by 1.18s. The outliers for L2 Trigger in Figure 6.4 occupy a range of approximately 500ms which is also the random solicited RA de-

[8] 24 at the time of writing
[9] l2trig in all figures and tables

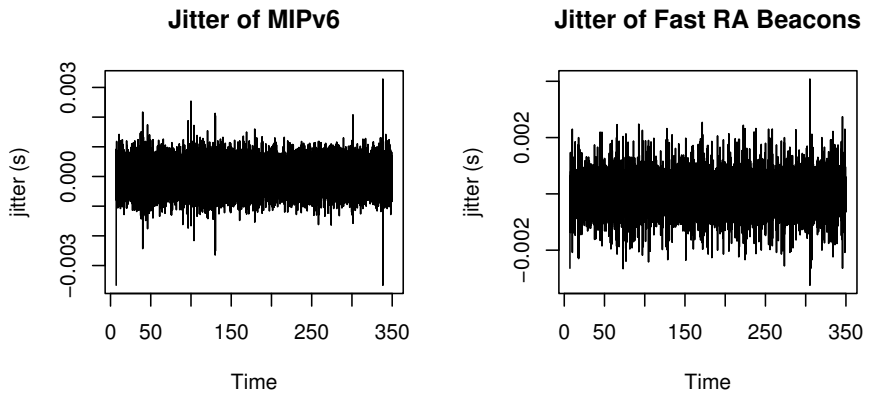


Figure 6.7: Jitter comparison between MIPv6 and MIPv6 with Fast RA beacons. The plots are derived from taking the difference of the delay from previous measurement from the current one.

lay. When FSRA was combined with L2 Trigger the improvement over L2 Trigger by itself is 210ms. This is not the theoretical expected improvement of 250ms when we eliminate the uniform 0 - 500ms solicited RA delay. However the true means are bounded by the confidence interval limits and so the figure of 210ms is plausible too.

In Table II of [23] the results for a test bed experiment with L2 Trigger triggers are given. While the absolute value for their L2 Trigger without DAD is 234.96ms and my result for L2 Trigger-ODAD of 567ms grossly underestimates L2 Trigger-ODAD's handover performance. However their improvement by combining with FSRA was 218.56. This is very similar to the improvement in handover latency obtained from simulation of 212ms[10]. This shows that the simulation may not be correct in terms of absolute performance but is very accurate when comparing the relative performance between different handover schemes.

The "catalyst" for reducing rendezvous delay is thus L2 Trigger. L2 Trigger is easy to add to existing MNs as it requires only a software update to the MIPv6 stack to take advantage of a link-layer specific L2 Trigger since most L2 devices already provide L2 "link up" notification [23].

[10]From Table 6.1 L2 Trigger-ODAD(567ms) - L2 Trigger-ODAD-FSRA(355ms)

L2 Trigger is not a foolproof method of movement detection because if the MN roams between access points that are connected to the same interface on a router then the MN will mistakenly try to solicit responses from the same router thus causing unnecessary increases in traffic. One solution is to employ longer range access points with high capacity to serve more users. Nevertheless this slight increase in traffic is worth the great reduction in handover time.

6.1.6 AR Localised Extensions Combined

Rendezvous delay was identified as the major showstopper to reducing handover delay and either Fast RA beacons or L2 Trigger would act as the "catalyst" to reduce it effectively. The combination of L2 Trigger and FSRA for handover latency is close to Fast RA beacons the difference been 90ms as determined from Table 6.1. Fast RA beacons is more consistent in handover latency than L2 Trigger-FSRA as shown by the smaller IQR in Figure 6.4, This improvement and consistency in handover time for Fast RA beacons is due to the regular RAs that are sent and so there is no wireless delay roundtrip resulting from the RS and RA exchange that occurs from using FSRA. It may be too consistent though as a result of the reduced number of handovers recorded. The Fast RA beacon handover optimisation was not considered any further[11] in the experiment mainly because I thought that the many RAs would increase the (end-to-end delay) of data packets on the shared wireless medium as discussed at Section 6.1.4. In hindsight I realise that Fast RA beacons is a constant overhead regardless of the number of MNs while the combination of L2 Trigger and FSRA will increase linearly[12] in overhead with the number of MNs. Without further experimentation I hesitate to dismiss Fast RA beacons straight away.

Once the L2 Trigger "catalyst" is brought in, ODAD begins to show its true potential. Table 6.1 shows the improvement of 863ms for L2 Trigger-ODAD over L2

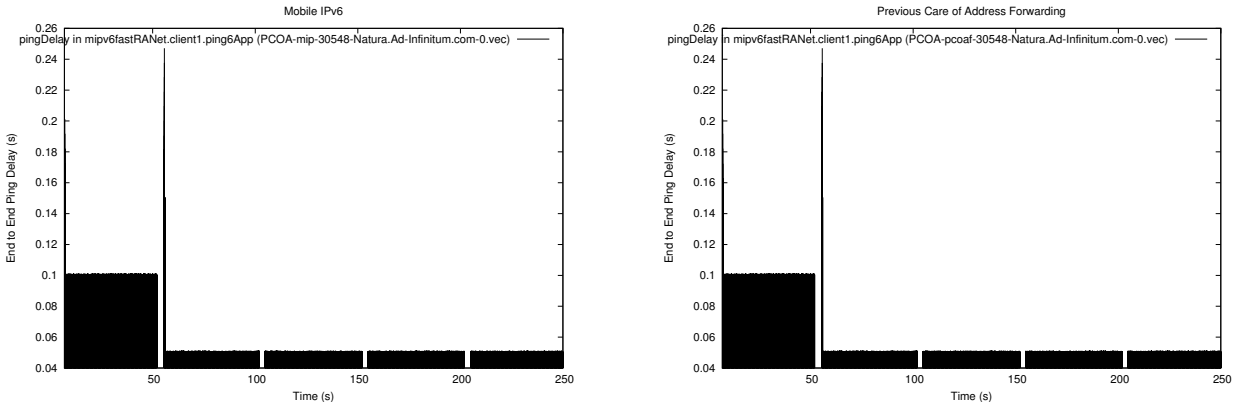
[11] By combining it with ODAD. The expected improvement would be close to one second anyway.

[12] this would depend on how many MNs arrive at a link sequentially one after another, in such a manner that each MN has just missed the previous solicited RA and so sends another RS

Trigger by itself. This is close to the fabled one second improvement due to the elimination of DAD. FSRA also shows a similar dependent behaviour on L2 Trigger. When comparing performance of L2 Trigger-FSRA and L2 Trigger there is an improvement of 210ms. The same improvement is also seen when comparing L2 Trigger-ODAD to L2 Trigger-ODAD-FSRA. This nonlinear behaviour of the AR-local extensions not showing the expected improvement on an individual basis is because FSRA and ODAD have to be activated early in order to be of use and that activation comes from the MN been aware that it has moved. This is provided by the L2 Trigger "catalyst".

I believe the ideal combination of AR-local extensions are FSRA, L2 Trigger, ODAD and Fast RA beacons may offer the fastest handovers because FSRA allows a node to solicit a response if it has not received a RA yet after getting an L2 indication. The RA interval parameter in Fast RA beacons is reduced to some point before FSRA becomes redundant and also greater than some threshold to prevent the collisions on the shared wireless medium from getting out of hand. However this setting would be different for every network depending on the arrival rate of MNs and the particular L2 technology's wireless delay. As a compromise just deploying standard MIPv6 in its default configuration and adding L2 Trigger, ODAD and FSRA extensions should be enough to ensure basic real-time services such as VoIP with some robust codec to have a seamless handover. For higher quality real-time traffic some form of buffering will have to be employed during handover to reduce packet loss as five dropped packets per handover as shown in Table 6.2 is probably too much for the codec to handle since the performance in the real network would be worse as the results were collected in an optimised simulated environment of local movement close to the HA and assuming no errors in wireless transmission medium. Alternatively the codec would have to be improved or a different wireless transmission medium besides IEEE 802.11 which allows make before break type of handovers.

The AR-local extensions as presented here cannot reduce the latency of the 1st handover, when moving away from home as discussed in Section 5.2. It was not



(a) Plot of end-to-end delay for MIPv6.

(b) Plot of end-to-end delay for PCoAF.

Figure 6.8: Plot of end-to-end delay for $d_{Internet}$ of 50ms.

necessary to simulate this because we know the result is more than a second increase for handover latency since DAD takes that long by default.

6.2 Previous Care of Address Forwarding

In Figure 6.8 the end-to-end delay is plotted for both MIPv6 and PCoAF. From the comparison of the two figures it is clear that PCoAF does not alter the end-to-end delay. This is to be expected since PCoAF is only activated just after handover and lasts for a short period of time only[13]. The processing and forwarding delays[14] between the interfaces in the AR are negligible compared to the propagation delay between the AR and the HA or CN.

Figure 6.9 shows that PCoAF does not have an affect at the first handover. This is in accordance with the expected behaviour as PCoAF does not occur unless the handover is from a foreign link to another foreign link or back home. For the first handover when the MN moves away from home, it would not make sense to send a separate BU to the HA for PCoAF purposes when a BU is already sent to the HA as part of the base MIPv6 protocol. Thus for discussion purposes and all the plots that

[13] 5 seconds for binding with PAR

[14] propagation delay if many ARs were simulated instead of one AR with many interfaces

are drawn now data from the first handover is excluded.

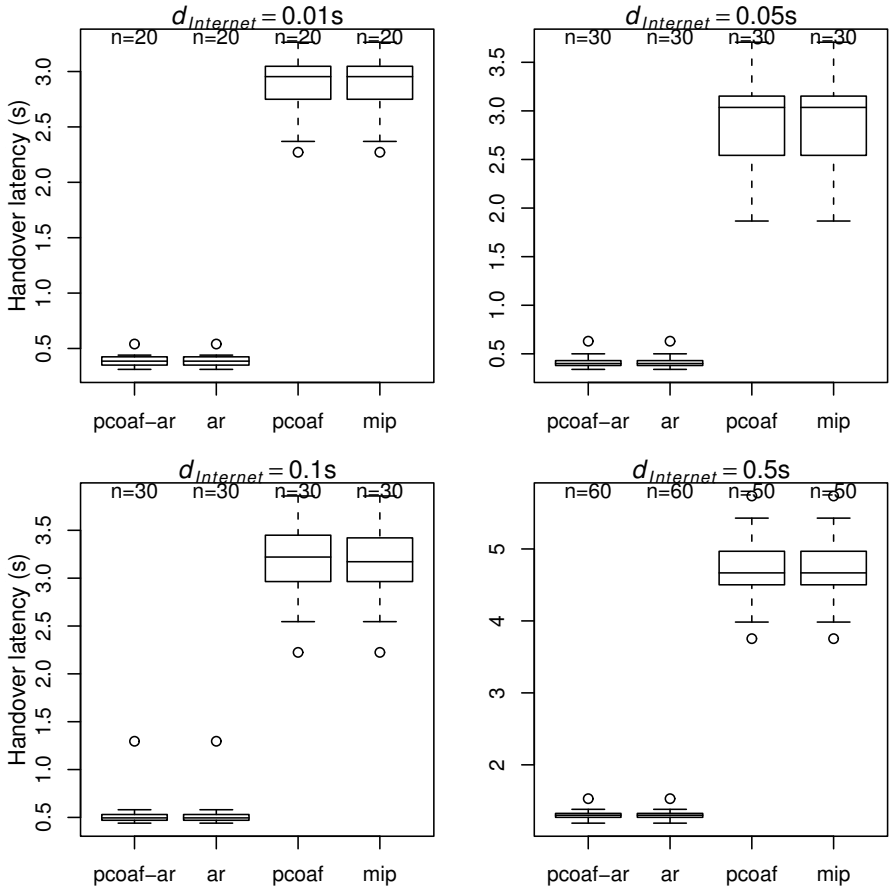


Figure 6.9: Comparison of handover latency at 1st handover between when PCoAF is enabled and disabled for MIPv6 and AR-local extensions combined.

The general trend as shown in Figure 6.10 is that an increase in propagation delay $d_{Internet}$ does not affect handover latency or packet loss of the PCoAF-AR[15] combination at all. Note again how the packet loss is linearly related to the handover latency (see Section 6.1 for an explanation). PCoAF by itself is susceptible to decreasing handover performance with increasing $d_{Internet}$ although not to such an extent as MIPv6. A similar relationship is seen when AR-local extensions are in use and when the PCoAF is disabled the handover performance also suffers as $d_{Internet}$ increases. As to why the combination of PCoAF-AR is able to arrest the

[15]AR in this context stands for the combination of three AR-local extensions ODAD, L2 Trigger and FSra that was analysed in Section 6.1.6

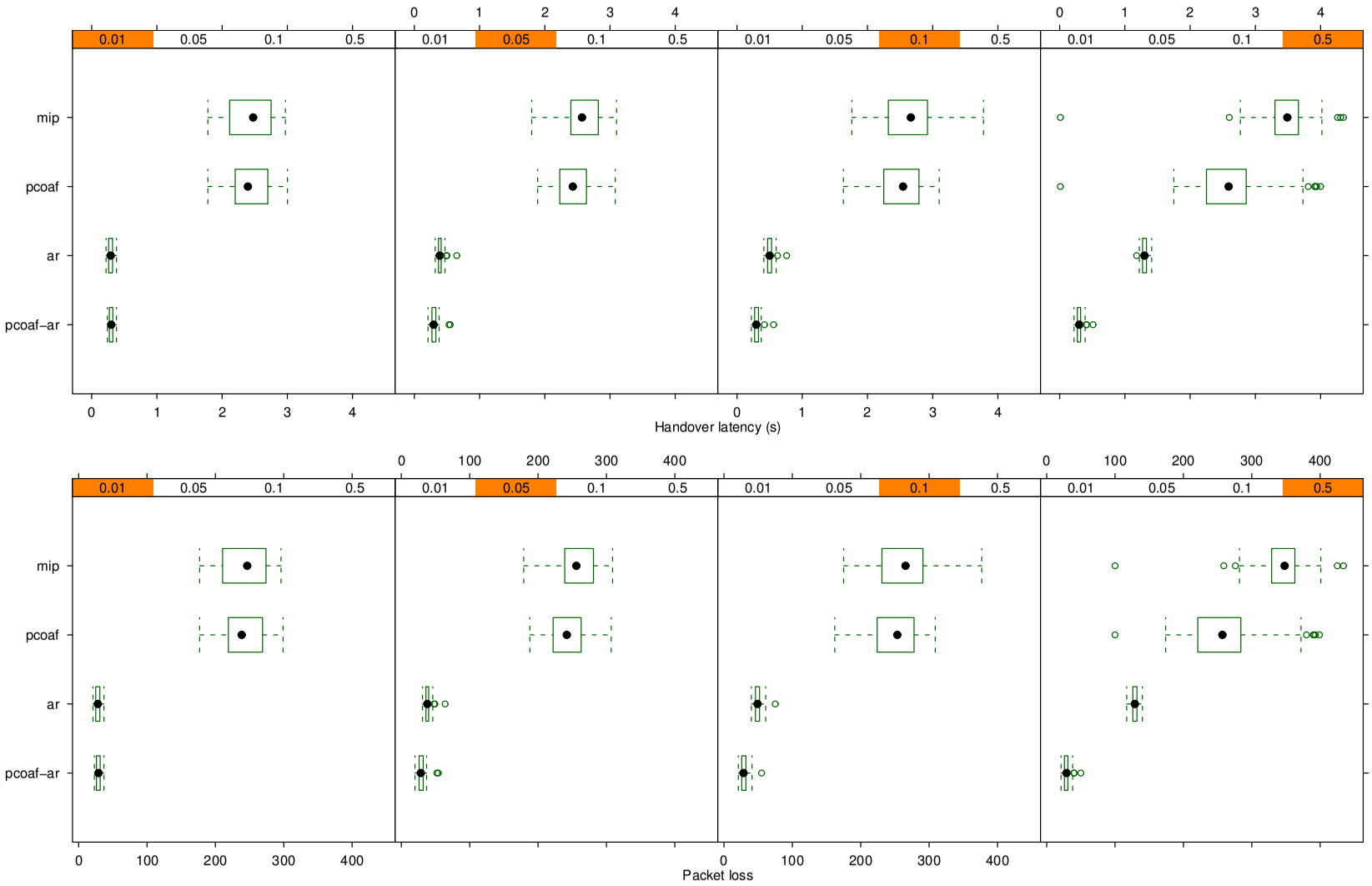


Figure 6.10: Conditional plot of handover latency (top) and packet loss (bottom) against handover schemes for different $d_{Internet}$

handover performance degradation due to increasing propagation delay is because the AR-local extensions allow the MN to resume communications as soon as possible after L2 handover by sending a BU to the PAR which is topologically much closer than the HA and so packets are forwarded and saved from oblivion much earlier. As the path delay to the PAR is less than $d_{Internet}$ it has bought some time for the MN to register with the HA to keep the route optimised and minimise changes to the end-to-end delay. PCoAF by itself is not able to do this as well because it takes too long for it to setup a CoA from the NAR and so the number of packets that it can save are severely limited. However it should still maintain the same handover performance though given all other things been equal. Looking at the confidence interval limits for PCoAF in Table 6.3, Table 6.4, Table 6.5, and Table 6.6 it is clear that the population mean for all of these overlap[16] and so we cannot say with 95% confidence that the results differ.

	No. of Handovers	Mean	Lower CI limit	Upper CI limit
pcoaf-ar	60	2.99e−01	2.89e−01	3.09e−01
ar	60	2.92e−01	2.82e−01	3.01e−01
pcoaf	60	2.42e+00	2.34e+00	2.51e+00
mip	60	2.45e+00	2.36e+00	2.53e+00

Table 6.3: Mean and CI of handover latency for PCoAF experiment with $d_{Internet} = 0.01s$

	No. of Handovers	Mean	Lower CI limit	Upper CI limit
pcoaf-ar	90	3.03e−01	2.92e−01	3.14e−01
ar	90	3.95e−01	3.85e−01	4.04e−01
pcoaf	90	2.47e+00	2.40e+00	2.53e+00
mip	90	2.58e+00	2.52e+00	2.65e+00

Table 6.4: Mean and CI of handover latency for PCoAF experiment with $d_{Internet} = 0.05s$

[16]Only the upper limit of PCoAF for $d_{Internet}$ of 0.01s in Table 6.3 and lower limit for $d_{Internet}$ of 0.5s in Table 6.6 are off by 0.01s

	No. of Handovers	Mean	Lower CI limit	Upper CI limit
pcoaf-ar	90	2.97e−01	2.86e−01	3.07e−01
ar	90	4.97e−01	4.87e−01	5.08e−01
pcoaf	90	2.51e+00	2.44e+00	2.58e+00
mip	90	2.63e+00	2.55e+00	2.71e+00

Table 6.5: Mean and CI of handover latency for PCoAF experiment with $d_{Internet} = 0.1s$

	No. of Handovers	Mean	Lower CI limit	Upper CI limit
pcoaf-ar	180	2.98e−01	2.92e−01	3.04e−01
ar	180	1.30e+00	1.30e+00	1.31e+00
pcoaf	153	2.61e+00	2.52e+00	2.69e+00
mip	153	3.46e+00	3.39e+00	3.52e+00

Table 6.6: Mean and CI of handover latency for PCoAF experiment with $d_{Internet} = 0.5s$

6.3 Hierarchical Mobile IPv6

In Section 6.2 we had established that PCoAF does not have an effect at the 1st handover. HMIPv6 according to the draft should bind with the MAP first and then bind with the HA using RCoA as CoA. Based on this interpretation it would appear that MIPv6 should be faster. Figure 6.11 is a comparison of the handover latency at the 1st handover. It appears as though they are at least equal based on the medians and the overlap of the notches[17]. The size of the notches are quite large compared to the IQR and so the number of handover samples collected were really inadequate. At this stage all that can be said is that they are the same based on the results presented in the figure.

The reason for appearing to be equal to MIPv6 can be explained by the fact that in my simulation there is no DAD of the RCoA at the MAP. Thus about the only difference between the draft and my implementation is that HMIPv6 goes through

[17]An anomaly exists for the last pair of box plots where RR is better than MIP and vice versa. However the sample size is too small and so wide variations are common.

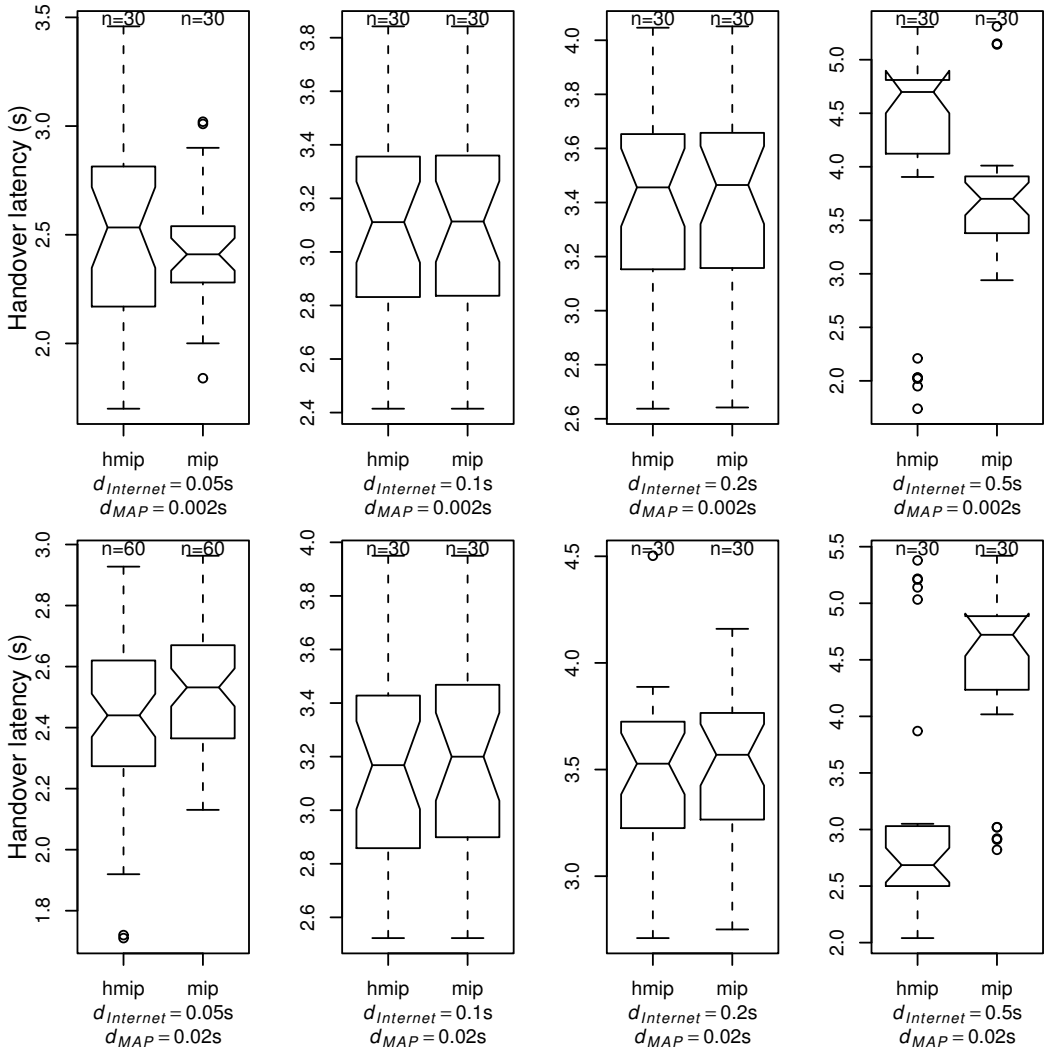


Figure 6.11: Comparison between HMIPv6 and MIPv6 at 1st handover

MAP first and waits for reply while my implementation does not have to wait long for a reply and can bind with HA and CN quickly. A d_{MAP} of 0.02s is not large enough to show that MIPv6 is faster at handover than HMIPv6 for the first handover.

Looking at packet loss shown in Figure 6.13 we can conclude that there is a linear relationship between packet loss and handover latency again. Thus the comments on handover latency in this section are equally applicable to packet loss too.

The bottom row of box plots in Figure 6.12 shows that HMIPv6 and PCoAF

have the same handover latency performance characteristic of being able to remain constant oblivious to the changes in propagation delay of $d_{Internet}$. The numbers HMIPv6 or PCoAF in Table 6.7, Table 6.8, Table 6.9, Table 6.10 confirm this as the CI limits overlap when $d_{Internet}$ increases. HMIPv6 seems to be better than PCoAF according to the mean handover latency but for $d_{Internet}$ of 0.02s in Table 6.9 and 0.05s in Table 6.10, the CI limits overlap so we cannot state that HMIPv6 is superior as the number of handover samples are inconclusive. Visually the first three panels of bottom row of Figure 6.12, HMIPv6's median handover was less than PCoAF and for the last panel HMIPv6 was more consistent with less range between the extent of the whiskers compared with PCoAF.

However when d_{MAP} was increased to 0.02s as depicted in the top row of Figure 6.12 and shown in Table 6.11,Table 6.12, Table 6.13 and Table 6.14, the performance for PCoAF handover latency appears to have caught up with HMIPv6 from looking at the mean handover latency in the tables and the median in the box plots. The CI limits shown in those tables show that PCoAF and HMIPv6 are equal as there is an overlap except for the $d_{Internet}$ of 0.005 in Table 6.11 where PCoAF is clearly superior. So HMIPv6 handover latency is clearly dependent on the size of the MAP domain i.e. how high in the MAP hierarchy it registers with, because the BU to the MAP will take at least d_{MAP} seconds to reach there. Had we simulated a bigger MAP domain with say a d_{MAP} of 0.2s I am certain this effect will be more pronounced. PCoAF is not affected at all and treats d_{MAP} as just an additional component to $d_{Internet}$ since it registers with the PAR temporarily whilst the BU travels to HA or CNs.

When considering only handover latency and packet loss PCoAF is the superior solution as it does not require MAP functionality and is a simpler algorithm (no need to determine who to register with unlike HMIPv6). In fact with the default behaviour of HMIPv6 always choosing the furthest MAP, PCoAF will always be the same as or faster at handoff than HMIPv6. The only advantage that comes from

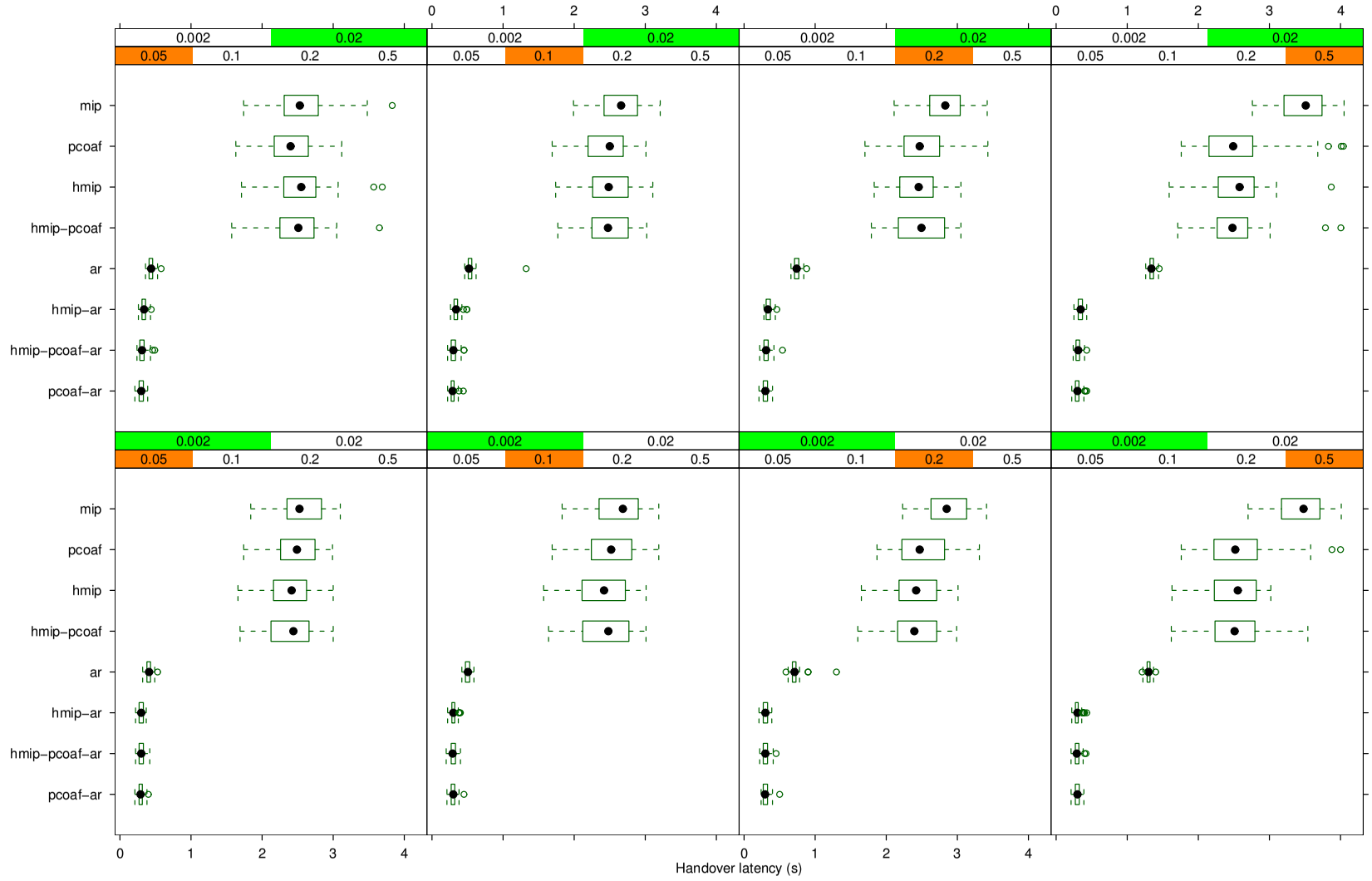


Figure 6.12: Conditional plot of handover latency against handover schemes for different propagation delays. The lower shingle is $d_{Internet}$ and upper shingle is d_{MAP}

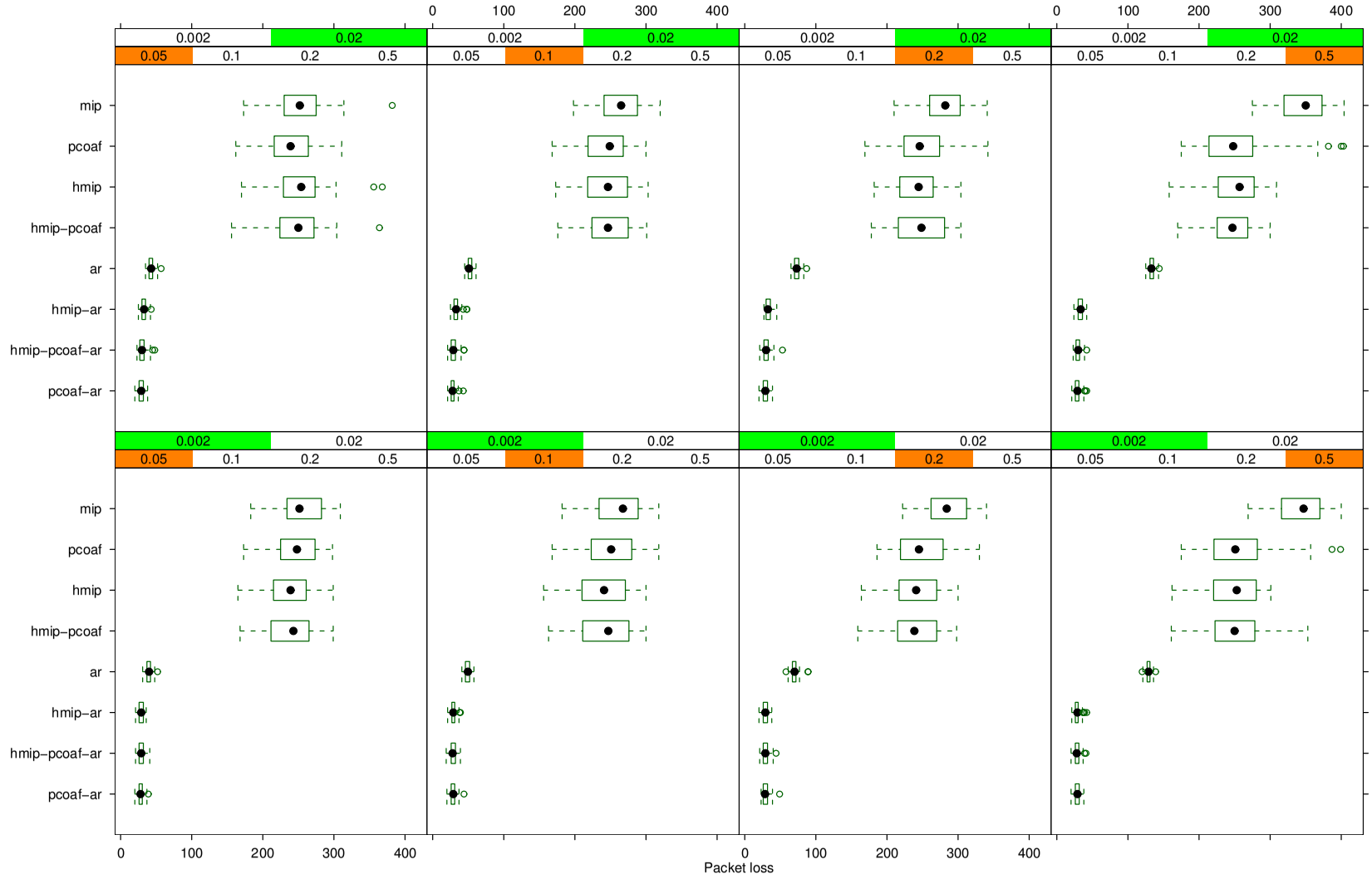


Figure 6.13: Conditional plot of packet loss against combinations of handover schemes for different propagation delays in the HMIPv6 experiment. The lower shingle is $d_{Internet}$ and upper shingle is d_{MAP}

using HMIPv6 is that there are less global bindings and so overhead should be less although with the tunnelling from MAP to MN the savings in overhead is eroded somewhat.

From these observations I recommend the use of PCoAF at ARs instead of a MAP. Because a MAP at AR level has exactly the same effect as PCoAF in handover latency performance. There is no advantage of less global bindings with RR since moving to another subnet would need a MAP handover which necessitates a global binding too. Forwarding from previous MAPs will reduce the packet loss and uses tunnelling like PCoAF. However PCoAF is used temporarily during and after handover so normally there is no tunnelling overhead from normal data packets unlike HMIPv6 which always tunnels. Clearly then PCoAF is the superior choice at the AR level.

Considering the handover schemes that used the combination of AR-local handover extensions as shown in Figure 6.14, we see the same behaviour as the PCoAF experiment where the AR-local handover extensions by itself like MIPv6 is equally susceptible to the increasing propagation delay from $d_{Internet}$. The performance of all schemes whether they employed HMIPv6 or PCoAF or both was exactly the same when d_{MAP} is 0.002s which is shown at the bottom row of panels in Figure 6.14. This is confirmed by the overlap in the CI limits of HMIPv6-AR, PCoAF-AR and HMIPv6-PCoAF-AR as shown in Table 6.7,Table 6.8, Table 6.9 and Table 6.10. This time around the effect of increasing d_{MAP} to 0.02s as shown in Figure 6.14 for the top row of panels produces the expected HMIPv6 handover performance degradation that was only hinted at when AR-local extensions were not used. There is no overlap for the CI limits of the corresponding mean handover latency of HMIPv6-AR as shown in Table 6.11,Table 6.12, Table 6.13 and Table 6.14 where $d_{Internet}$ increased which confirms this visual observation.

From these observations we can conclude that RR-PCoAF-AR is the best scheme since it does not suffer from the vulnerability for packet loss and increase in han-

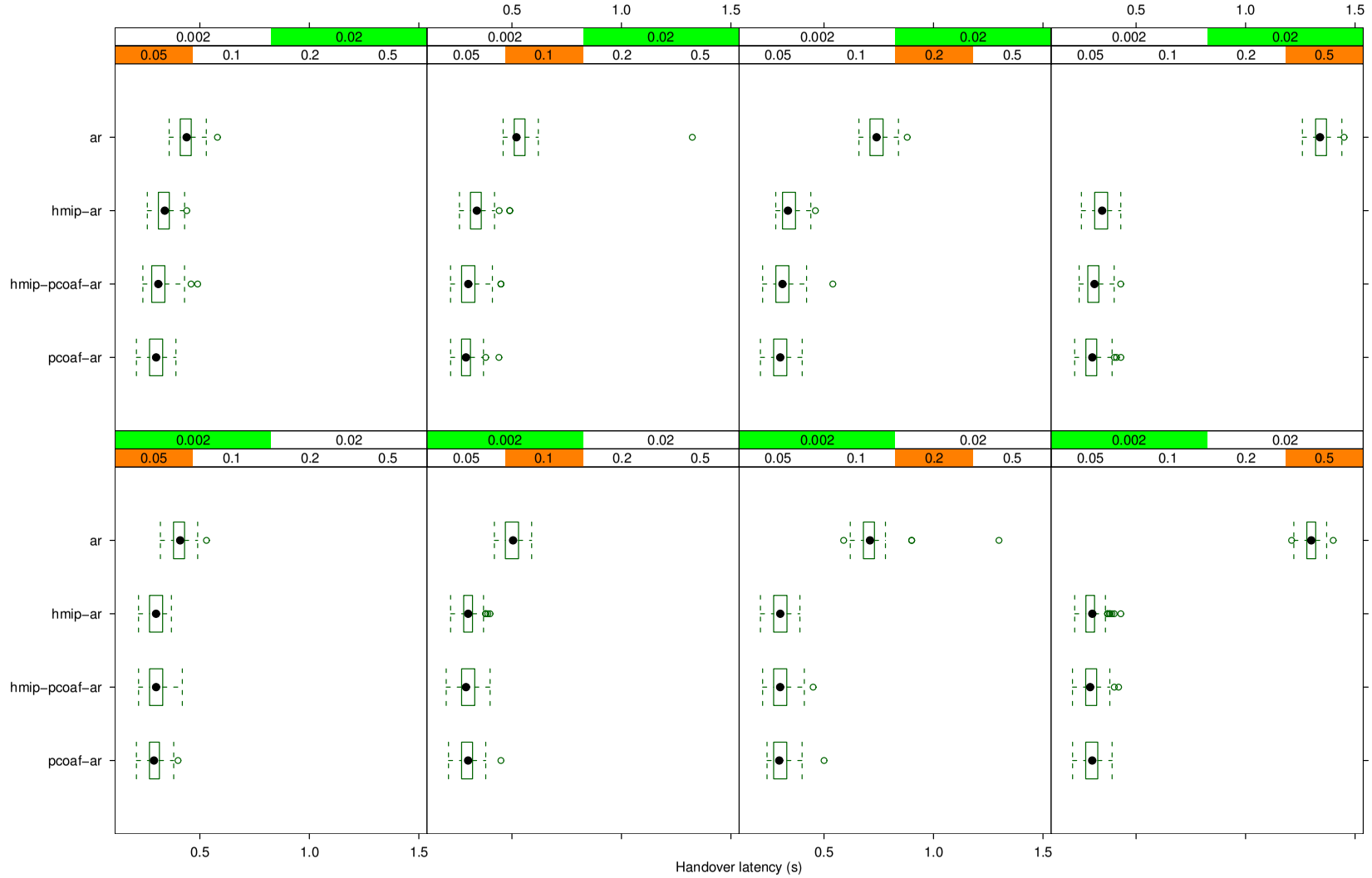


Figure 6.14: Same plot as Figure 6.12 except focusing only on combinations of AR-local extensions.

	No. of Handovers	Mean	Lower CI limit	Upper CI limit
pcoaf-ar	60	2.95e−01	2.84e−01	3.06e−01
hmip-pcoaf-ar	60	2.99e−01	2.88e−01	3.11e−01
hmip-ar	60	2.97e−01	2.86e−01	3.08e−01
ar	60	4.05e−01	3.94e−01	4.16e−01
hmip-pcoaf	60	2.40e+00	2.32e+00	2.49e+00
hmip	60	2.40e+00	2.31e+00	2.49e+00
pcoaf	60	2.48e+00	2.41e+00	2.56e+00
mip	60	2.56e+00	2.48e+00	2.64e+00

Table 6.7: Mean and CI of handover latency for HMIPv6 experiment with $d_{internet} = 0.05s$ and $d_{MAP} = 0.002s$

	No. of Handovers	Mean	Lower CI limit	Upper CI limit
pcoaf-ar	90	2.96e−01	2.87e−01	3.05e−01
hmip-pcoaf-ar	90	2.99e−01	2.90e−01	3.07e−01
hmip-ar	90	2.98e−01	2.90e−01	3.07e−01
ar	90	5.01e−01	4.93e−01	5.10e−01
hmip-pcoaf	90	2.47e+00	2.39e+00	2.55e+00
hmip	90	2.40e+00	2.33e+00	2.48e+00
pcoaf	90	2.52e+00	2.45e+00	2.59e+00
mip	90	2.64e+00	2.57e+00	2.71e+00

Table 6.8: Mean and CI of handover latency for HMIPv6 experiment with $d_{internet} = 0.1s$ and $d_{MAP} = 0.002s$

dover latency due to increasing d_{MAP}. It is better than PCoAF-AR only because it supposedly has reduced overhead arising from less global bindings although there is I assume a smaller increase in overhead too from the temporary double encapsulation from the MAP and the PAR just during and shortly after handover. RR-PCoAF-AR is suitable for deployment on any AN that uses HMIPv6 with an arbitrary MAP hierarchy. Of course as we noted earlier we should not deploy a MAP at the ARs. Further testing is required to see how much savings in overhead if any from the reduced global bindings and the increase in overhead of HMIPv6 tunnelling and PCoAF tunnelling when the two are used together for some arbitrary topologies and different mobility patterns.

	No. of Handovers	Mean	Lower CI limit	Upper CI limit
pcoaf-ar	90	2.98e−01	2.89e−01	3.07e−01
hmip-pcoaf-ar	90	2.98e−01	2.89e−01	3.07e−01
hmip-ar	90	3.01e−01	2.92e−01	3.10e−01
ar	90	7.15e−01	6.99e−01	7.32e−01
hmip-pcoaf	84	2.42e+00	2.34e+00	2.49e+00
hmip	90	2.43e+00	2.36e+00	2.50e+00
pcoaf	90	2.50e+00	2.42e+00	2.58e+00
mip	90	2.86e+00	2.79e+00	2.92e+00

Table 6.9: Mean and CI of handover latency for HMIPv6 experiment with $d_{internet} = 0.2s$ and $d_{MAP} = 0.002s$

	No. of Handovers	Mean	Lower CI limit	Upper CI limit
pcoaf-ar	87	2.96e−01	2.87e−01	3.05e−01
hmip-pcoaf-ar	90	2.95e−01	2.86e−01	3.03e−01
hmip-ar	90	3.00e−01	2.91e−01	3.08e−01
ar	90	1.30e+00	1.29e+00	1.31e+00
hmip-pcoaf	75	2.49e+00	2.40e+00	2.58e+00
hmip	72	2.50e+00	2.42e+00	2.59e+00
pcoaf	81	2.56e+00	2.46e+00	2.65e+00
mip	81	3.44e+00	3.36e+00	3.52e+00

Table 6.10: Mean and CI of handover latency for HMIPv6 experiment with $d_{internet} = 0.5s$ and $d_{MAP} = 0.002s$

A simple mathematical analysis of the handover latency between basic MIPv6, anticipated FMIP, HMIPv6 and both combined by the authors in [73] found that whilst HMIPv6 performs better than FMIP when the wired link delay was much less than the wireless link delay, FMIP provided smoother handover by ensuring less packet losses. HMIPv6 in comparison to MIPv6 not only reduced signalling to HA and CNs but can also help to reduce handover latency. Their recommendation was that combining both FMIP and HMIPv6 can result in the greatest latency reduction. Otherwise they believe that FMIP is slightly better than HMIPv6 if only one enhancement beyond base MIPv6 mobility is allowed.

These are all statements which agree with my simulation results if you replace

	No. of Handovers	Mean	Lower CI limit	Upper CI limit
pcoaf-ar	168	3.02e−01	2.95e−01	3.08e−01
hmip-pcoaf-ar	180	3.13e−01	3.06e−01	3.19e−01
hmip-ar	183	3.38e−01	3.33e−01	3.44e−01
ar	180	4.36e−01	4.30e−01	4.42e−01
hmip-pcoaf	180	2.49e+00	2.44e+00	2.54e+00
hmip	180	2.54e+00	2.49e+00	2.58e+00
pcoaf	177	2.41e+00	2.37e+00	2.46e+00
mip	165	2.55e+00	2.50e+00	2.60e+00

Table 6.11: Mean and CI of handover latency for HMIPv6 experiment with $d_{internet} = 0.05s$ and $d_{MAP} = 0.02s$

	No. of Handovers	Mean	Lower CI limit	Upper CI limit
pcoaf-ar	90	2.92e−01	2.84e−01	3.01e−01
hmip-pcoaf-ar	90	3.06e−01	2.96e−01	3.17e−01
hmip-ar	90	3.38e−01	3.28e−01	3.47e−01
ar	90	5.40e−01	5.20e−01	5.59e−01
hmip-pcoaf	90	2.48e+00	2.41e+00	2.55e+00
hmip	90	2.49e+00	2.42e+00	2.56e+00
pcoaf	87	2.46e+00	2.39e+00	2.53e+00
mip	90	2.65e+00	2.59e+00	2.71e+00

Table 6.12: Mean and CI of handover latency for HMIPv6 experiment with $d_{internet} = 0.1s$ and $d_{MAP} = 0.02s$

FMIP with AR-local extensions. Their recommendation was HMIPv6 with FMIP and my recommendation is HMIPv6 with PCoAF and AR-local extensions. They implicitly used PCoAF since there measurement of handover latency involved data packets forwarded from PAR too[18]. AR-local extensions is I believe close to FMIP in performance without the complexity and is actually implemented in test beds already although perhaps not all combined yet[19] [23, 71]. While HMIPv6 with FMIP has been tested in lab environments [74], the authors do claim it is ready for deployment yet. Even if HMIPv6 proves too difficult to deploy[20] the combination of AR-local

[18]This paper was before PCoAF was officially removed from the MIPv6 draft

[19]ODAD has already been implemented in Linux kernel and in some embedded system. Contact the author of [39] for further details.

[20]in determining where to put the MAPs and configuring MAP domain sizes

	No. of Handovers	Mean	Lower CI limit	Upper CI limit
pcoaf-ar	90	3.00e−01	2.92e−01	3.09e−01
hmip-pcoaf-ar	90	3.12e−01	3.02e−01	3.23e−01
hmip-ar	90	3.38e−01	3.29e−01	3.47e−01
ar	90	7.39e−01	7.28e−01	7.49e−01
hmip-pcoaf	90	2.48e+00	2.41e+00	2.56e+00
hmip	90	2.45e+00	2.39e+00	2.52e+00
pcoaf	90	2.50e+00	2.42e+00	2.58e+00
mip	90	2.82e+00	2.75e+00	2.88e+00

Table 6.13: Mean and CI of handover latency for HMIPv6 experiment with $d_{internet} = 0.2s$ and $d_{MAP} = 0.02s$

	No. of Handovers	Mean	Lower CI limit	Upper CI limit
pcoaf-ar	90	3.00e−01	2.92e−01	3.09e−01
hmip-pcoaf-ar	90	3.06e−01	2.97e−01	3.14e−01
hmip-ar	90	3.44e−01	3.36e−01	3.52e−01
ar	90	1.34e+00	1.33e+00	1.35e+00
hmip-pcoaf	75	2.49e+00	2.40e+00	2.58e+00
hmip	75	2.57e+00	2.48e+00	2.65e+00
pcoaf	75	2.51e+00	2.40e+00	2.63e+00
mip	75	3.47e+00	3.39e+00	3.55e+00

Table 6.14: Mean and CI of handover latency for HMIPv6 experiment with $d_{internet} = 0.5s$ and $d_{MAP} = 0.02s$

extensions with PCoAF is probably the most effective and deployable solution at reducing L3 handover delay for the moment. Without regards to the security issues involved, I propose that MIPv6 be modified to allow short BU intervals without the prior security association only when the MN wants to bind briefly for PCoAF purposes[21]. Since L2 Trigger would require modification to the MIPv6 stack I do not believe this task is onerous.

The authors in [74] have found that for TCP traffic the expected gains from combining many different handover techniques may not occur. My own results from the simulation show that for certain L3 handover improvement techniques these

[21] perhaps another flag can be added explicitly for this very purpose

do combine to improve handover latency as long as L2 Trigger is used and gives the expected improvement when ping traffic was used[22]. This would apply also to traffic of the streaming multimedia variety where the user connects to a server and either is added to a multicast group or is sent a stream of UDP packets.

I believe HMIPv6 can be improved by combining with PCoAF at the AR level instead of MAPs as explained previously. Especially when the MN has a low transition rate it should not even register with any MAP and only do so when it has a higher transition rate.

6.4 Problems with Route Optimisation

Route optimisation is a fragile process since the wireless network is very lossy and the BU to CN can be lost and so there is no way of recovery especially when BUs to CN are unacknowledged by default, so no retries occur. This is a problem with route optimisation because once it is used the bindings need to be updated at every handover or the binding deleted. Otherwise the CN will address packets to previously visited subnets until the binding entry times out. Since most applications do not and should not have explicit mobility support, the application at the MN will not know that the absence of packets from the CN is an indication of an outdated binding cache entry at the CN and all that is required is to update the CN's binding cache.

The method used in MIPL to deal with this anomaly is to keep a count of how many ICMP destination unreachable messages are received for the MN's outdated CoA. When this count reaches a configurable limit the binding cache entry is removed.

This requires a considerable amount of time considering the routers will use standard NUD mechanism to determine that the MN is no longer reachable at that

[22]For PCoAF and HMIPv6 experiment the MN just recorded ping requests from the CN and so is very similar to User Datagram Protocol (UDP) traffic.

point. My recommendation is to always turn on acknowledgements for all BUs if reliable delivery of packets and minimal packet loss is a priority.

[28] argues that it is not always efficient to perform route optimisation. Thus he has devised an algorithm taking into account signalling and link costs to determine when it is advantageous to turn on RO. If RO is not turned on then can use the smooth handoff in MIP or previous MAP's CoA binding in HMIPv6 to forward packets from old subnet i.e. using the suboptimal routing path. Using some unit link cost assumptions the analysis shows that this model outperforms the model that always performs RO and plain MIP which never performs it according to total cost. While he applied this idea to MIP it applies equally to MIPv6 too. However this research is still in preliminary stages so whether it is possible to determine these link and signalling costs accurately enough in real deployment situations in order for MN to make the right decisions is unknown.

Chapter 7

Conclusions and Recommendations for Future Work

7.1 Conclusions

As 4G networks will have many pico-cellular networks for Personal Communication System (PCS), cell sizes will decrease causing an increase in the number of handovers [6], the IP layer hand-off will be dominant source of latency as shown in Chapter 3 so this needs to be fixed before causing unacceptable degradation to real-time traffic and terminating the session.

I have set out to do a performance evaluation of some mobility management protocols in order to see if the different components for L3 handover delay could be reduced. Using simulation, I have succeeded in showing that the correct combination of AR-local extensions which were L2 Trigger, ODAD and FSRA can prove beneficial in reducing handover delays from the standard MIPv6 handover delay of 2.6s to around 350ms as shown in Table 6.1 . For further details please refer to Section 6.1.

The single most beneficial AR-local extension would be L2 Trigger although Fast RA beacons is the quickest to deploy since it just requires changing some variables in the AR and is suitable for at least sparsely populated coverage areas.

To combat the vast distances of the Internet and variable network congestion an LMM protocol, HMIPv6 was also evaluated to see how effective it was in mitigating the effects of path delay. Two experiments were conducted one involving HMIPv6 and the other PCoAF. While PCoAF is technically an AR-local extension it is also able to keep the handover latency constant while the network delays increased and so can also be considered as a partial LMM protocol even though it does not reduce the number of global bindings.

I have also found that HMIPv6 is not really suitable for deployment on ARs i.e. the MAP role should not be enabled in the AR at all because PCoAF can achieve the same or better handover performance in terms of handover latency and packet loss without the overhead from tunnelling that occurs in HMIPv6. There may be security issues associated with this since PCoAF has been removed from the MIPv6 draft but my suggestion in Section 6.2 can be used to overcome this problem.

The best approach in terms of simplicity and ease of deployment in any arbitrary network access network would be to use the AR-local extensions combined with PCoAF because this gives the best performance for the least amount of investment required. These do not require more infrastructure than ARs with HA functionality and to have the MIPv6 modified slightly to allow PCoAF, FSRA and L2 Trigger to work. ODAD requires only changes on the MN.

Deploying any LMM solution like HMIPv6 right now is not guaranteed to scale simply because they are not mature enough and require a lot of upfront investment in terms of purchasing ARs with LMA functionality and deciding where to place them. There is no automated method of deployment and the LMA selection algorithms are still very much in there infancy as discussed in Section 4.3. Thus I can only recommend LMM investment in the AN only for testing and research purposes. With

the limited amount of MNs currently in use right now just deploying PCoAF with AR-local extensions should fulfil the demand for faster handovers and will not clog up the Internet with global bindings yet. While the handover latency is perhaps not fast enough for demanding multimedia applications with the advances in codecs and reduction in L2 handover times the future of a multimedia on the go is inevitable.

This thesis has resulted in an original contribution in the following ways:

- IPv6Suite, an accurate simulation suite for IP protocols for WLAN networks released to the research community under GPL license.
- The effects of DAD are fully taken into account in all simulations contrary to other simulations that do not take DAD seriously. It is the only simulation I know that uses Optimistic DAD to realistically reduce handover times as the mobile nodes in the real networks would have to implement in order to reduce L3 handover times and at the same time ensure address duplication does not occur on a link.
- Full MIPv6 compliance to draft 24 with reverse tunnelling, and route optimisation[1].
- HMIPv6 implementation compliant with the draft
- The only quantitative evaluation of previous CoA forwarding achieved using simulation.
- The only simulation that takes all the different handover improvement techniques and combines them into one simulation to evaluate their combined effects.
- Statistical validity was not sacrificed and all results have been plainly stated with the confidence interval limits stated. Please see [64] on the appalling track

[1] return routability and Dynamic Home Agent Address Discovery is not implemented yet

record of credibility of results obtained from telecommunications simulative studies.

7.2 Recommendations for Future Work

Recommended topics for future research are:

- Compare Ad-hoc to plain WLAN networks and get quantitative results on relative performance in simulation.
- MIPv6 integration with Ad-hoc networks, to allow ad-hoc nodes[2] to connect to the Internet via infrastructured nodes [75].
- LMA discovery process by MN and distribution of LMA presence for proper load balancing of LMA and traffic engineering purposes [51, 76].
- MPLS based LMM protocol performance evaluation using simulation [8].
- Many more MNs communicating simultaneously at random with realistic and large topologies generated by Brite with different mobility models.
- Future simulations should measure overhead from different handover schemes i.e. data payload/every bit of data transmitted on a per station basis and for the overall network. Many more output variables as described in [66]. This ensures that the simulation run is not wasted and a detailed view is obtained for analysis.

[2] free from AP

Appendix A

Design of IPv6Suite Simulation model

Refer to our paper[1] [55] for an introductory description to the IPv6Suite simulation model.

This chapter provides an in-depth tour of the major components in the IPv6Suite network layer depicted in Figure A.2 from a design perspective.

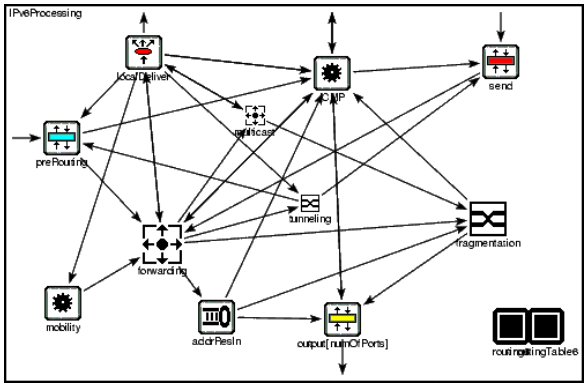


Figure A.1: IPv6Suite network layer components

In OMNeT++ there is a one to one correspondence between the simple module and the C++ class that implements that simple module's interface. However the behaviour of an IP stack is quite complex and so in our case some IP layer components have a one to many relationship. A primary class is defined as one that fulfils OMNeT++'s requirement of requiring an implementation for the simple module declaration by descending from cSimpleModule. The primary class in turn delegates some of its major tasks to other classes to get its job done. While it would be possible to place everything into the one class this is not manageable from a coding point of view. The relationships are depicted in the table below for the major IP layer components.

[1] *This paper has been included in the CDROM.*

Primary Class	Dependency on
NeighbourDiscovery	NDState and descendants(NDStateHost, NDStateRouter, MIPv6NDStateHost, MIPv6NDStateRouter, HMIPv6NDStateHost, HMIPv6NDStateRouter)
IPv6Mobility	MIPv6MobilityState and descendants
RoutingTable6	AddressExpiryTmr, ExpiryEntryList <RouterEntry>, ExpiryEntryList<PrefixEntry>,
IPv6Forward	HdrExtRteProc,HdrExtFragProc,HdrExtDestProc
IPv6Encapsulation	Callback function to validate tunnelled packets(supplied by MIPv6NDStateHost currently)

Table A.1: IPv6Suite Primary class Dependencies

A.1 IPv6Suite Network Layer Modules

A.1.1 RoutingTable6

show relationships between NC DC DRL MRL with diagrams

A.1.2 Encapsulation

Explain the flows in encapsulation that conforms to the requirements of the encapsulation RFC [33]. Describe the tunnelling data structure and how it is integrated into the CDS so that tunnels act like virtual interfaces(add listings).

A.1.3 Forwarding

Algorithm of conceptual sending and use of CDS from RoutingTable6

A.1.4 NeighbourDiscovery

comment on its complexity and the state pattern of converting from router to host which is not tested/used. But the inheritance hierarchy makes sense from the rfc point of view of required behaviour of different node types.

It is the only module that is encapsulated in two different simple modules mainly because so much happens as part of neighbour discovery (ND) i.e. the address resolution while it belongs to neighbour disc is really a separate process and while it can be implemented as one the ensuing module would certainly be very cluttered. the nd module actually handles the autoconfiguration during node startup and is the first place where all ICMP nd messages arrive first before deciding whether to forward it to addr res because the two share the same set of messages e.g. for DAD sometimes you do not want it to be forwarded to addr res if addr is tentative. Also

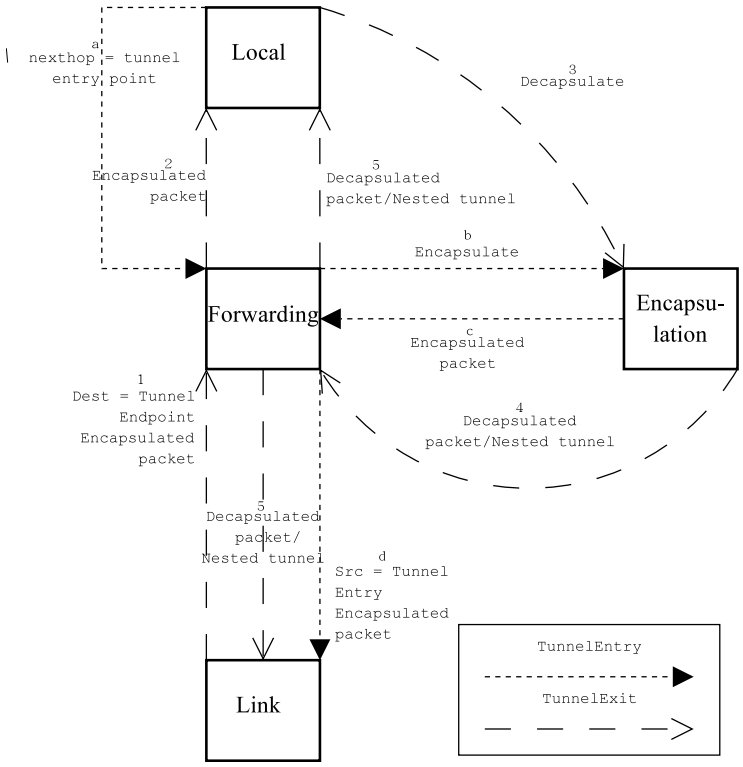


Figure A.2: Flow of datagrams in Encapsulation module of IPv6Suite

addrRess is just used by so many different modules to send packets so it is best not be stuck together with nd or in fact submodule of icmp.

A.1.5 IPv6Mobility

full conformance to 24 except no return routability procedure and IPsec support. Route Optimisation (RO) and reverse tunnelling done and specified per node level 2 types of movement detection L2 trigger or configurable no. of missedRtrAdvInterval. fast ras optdad hmip forwarding from previous coa

A.2 OMNeT++ Messages

Messages in our OMNeT++ models can be classified as been either network or self messages. Network messages are analogous to their real world counterparts often sporting data members similar to the Protocol Data Unit (PDU) descriptions in the corresponding RFC. Initially we tried to keep this "real" representation as a plain C data structure and then provide C++ wrappers around this. The advantage in doing this would be during the length computations and transferring the message into real packets for cosimulation[2] where the virtual network in the simulation would interact

[2]Using User Mode Linux (UML).

with a real network. However this was unnecessary at this stage and would delay the implementation. Thus there are inconsistencies in how the PDU's and their suboptions are declared in various header files i.e. IPv6Headers, ICMPv6Message, ICMPv6NDMessage, MIPv6MobilityHeaders, etc.

The term self message is given to messages that are sent from and received at the same simple module. They are usually used as timers in OMNeT++ simulations as this is the only method for adding a delay for simple modules that use the handleMessage format. They can also be used as a generic callback mechanism. This is necessary in many cases where one simple module relies on other simple modules' functions to aggregate more complex behaviour. A case in point is the MIPv6NDStateHost class runs in the context of the IPv6NeighbourDiscovery simple module. It receives notification of a handoff via a callback from either itself (IPv6NeighbourDiscovery) using the missed RA method or an L2 trigger from the IEEE 802.11b NIC module at the link layer. MIPv6NDStateHost will then call on IPv6Mobility module to send a BU on its behalf, the sending of the BU is coded in another callback and so a slight processing delay can be introduced.

A.3 OMNeT++ patterns

Common designs that were consistently used have been recorded here to help others navigate through our code.

A.3.1 Activity to HandleMessage Conversion

The complexity of the conversion depends on what features were used in the **activity** function. **receive()** and **receiveNewMsgOn** are some of the methods for receiving events in activity. In handleMessage the event is passed in as the sole argument to **handleMessage** function. For more information regarding activity and handlemessage differences OMNeT++ please consult the extensive user manual.

The first step which is applicable to all types of activity is to change all **continue** statements to **return**;

If only **wait()** was used in activity as shown in Listing A.1 then using a plain **cMessage** object is sufficient to simulate the wait. This object is *waitTmr* in the sample conversion shown in Listing A.2.

However if more than one message arrived simultaneously or while it is in the wait "state" these messages are just removed as shown at line 21 of Listing A.2. To maintain the same behaviour after conversion a **cQueue** object, *waitQueue* will have to be used to save these messages for further processing as **activity** does internally. This is shown in Listing A.3. To see this in action look at IPv6SendCore, IPv6OutputCore IPv6ForwardCore and ICMPv6Core units in **IPv6Suite/IP/IPv6/Generic** on the CDROM.

If **receiveNewOn** is used then will require searching through the *waitQueue* and also returning even if the message is not found because activity functions yield

Listing A.1: Typical activity function using **wait**

```
void IPv6Fragmentation::activity()
{
 while(true)
 {
   msg = receive();
   //op1()
   {
     ...
   }

   wait(delay);

   if (condition)
   {
     //op2()
     {
       ...
     }
     continue;
   }
   //op3()
   (
     ...
   )
 }// end while
}
```

back to other modules. I have noticed that a small delay is required in these cases otherwise it will continually schedule back to the module itself if delay of 0 is used. This is not a documented difference in OMNeT++. See the stripped down example in Listing A.4 for how this is done. Look at Enqueue and Dequeue units in **IPv6Suite/IP/IPv4/MAC_LLC/** on the CDROM for the complete and complex example.

My advice is to do it one module at a time and have the output of the old version stored in a file so we can verify that the **handleMessage** version does not deviate from the behaviour of the **activity** version. While these example listings do not show some complex versions where different delays could be used in **wait** or **wait** is called more than once and several receiveNewOns are called on different gates, if you just convert them separately using the basic principles shown here and in the correct order then the correct behaviour is guaranteed. An important point to note is that all activity functions yield which means that they allow other modules to get a share of the "time slice". If the simulation stops advancing time after conversion then you may have to insert some extra **return** statements and flags to indicate at what stage the code was up to so that it can return to that point once the **handleMessage** function is entered again.

Listing A.2: activity → handleMessage for **wait**

```
//Add waitTmr as protected member of class and a message variable
//curMessage to hold the message that will be processed later, after the
//wait

void initialize ()
{
  ...
  waitTmr = new cMessage("IPv6FragmentationWait");
  curMessage = 0;

}
void IPv6Fragmentation::handleMessage(cMessage* msg)
{
  if (!msg->isSelfMessage())
  {
    if (waitTmr->isScheduled()) //Outstanding wait
    {
      //Do whatever you want e.g. remove message, assert or see Listing A.3 for
      //details on saving it into a queue for processing later.
      delete msg;
      return;
    }else if (!waitTmr->isScheduled() && 0 == curMessage)
    {
      curMessage = msg;
      //op1();
      {
        ...
      }
      scheduleAt(delay + simTime(), waitTmr);
      return;
    }
    assert(false);
    return;
  }

  cMessage procMsg = curMessage;
  curMessage = 0;
  ///process procMsg
  if (condition)
  {
    //op2()
    {
      ...
    }
    return;
  }

  //op3()
  (
    ...
  )
}
```

Listing A.3: activity → handleMessage for **wait** with a *waitQueue* to handle simultaneous message arrivals

```
//Add waitQueue as data member in header file.
//After Listing A.2 line 10 add the following line
waitQueue.setName("ICMPv6WaitQ");

//Replace Listing A.2 line 21 with the following
waitQueue.insert(msg);


//Remove Listing A.2 line 38

//Append the following to the end of Listing A.2
if (waitQueue.empty())
  curMessage = 0;
else
{
  curMessage = boost::polymorphic_downcast<cMessage*>(waitQueue.pop());
  //op1();
  {
    ...
  }
  scheduleAt(delay + simTime(), waitTmr);
}
```

Listing A.4: activity → handleMessage when receiveNewOn is used

```
look at Enqueue and Deque
```

A.3.2 Callback pattern

Activity as we have noted before is a problem, because it is incompatible with debugging and memory validation tools and take up large amounts of stack space[3]. Thus all new modules are written in **handleMessage** format which is more complicated than activity when it comes to implementing delays. A naive first attempt would be to use a simple switch statement that calls different functions depending on what type of message was received. This results in rather large switch statements that are hard to maintain. The practice of defining unique message_id constants in some header file as we used to do for the IPv6NeighbourDiscovery unit and remembering to add a case statement to handle the new message type was error prone and tedious. Callback timer messages are a great alternative. They define the behaviour for handling that message type in one function and there is no requirement to add some code to invoke that particular callback except for the initial one. This makes the code appear a lot neater and clear although some opponents may complain it is hard to find which function handles what message type though. This information is only available at the creation of the callback timer instance.

[3] A simulation that required 32MB of stack to run before can now run under 8MB after conversion to handleMessage

Listing A.5: Callback pattern

```
void ICMPv6Core::handleMessage(cMessage* msg)
{
  if (msg->isSelfMessage())
  {
    //Invoke the callback
    msg->callFunc();
    return;
  }

  //Process Message from other modules
}
```

The callback timer classes all inherit from **cTimerMessage** because that was the interface for our callback mechanism. The pure virtual function callFunc() is redefined by them. Listing A.5 shows the general structure of all

We have defined many classes to assist in using this pattern. The full class hierarchy is shown in figure Figure A.3 I realised there were too many repetitions in

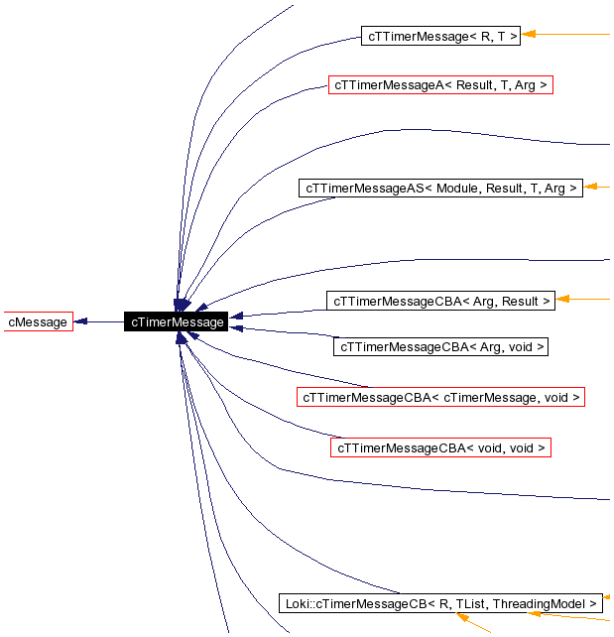


Figure A.3: Truncated *cTimerMessage* inheritance diagram showing template classes only [5]

terms of the common member functions in many of the callback classes been created. I started investigating using templates in order to achieve a more flexible solution. These attempts can also be seen from the inheritance tree of *cTimerMessage* in Figure A.3. Finally I discovered the powerful callback function abilities available from

[5] Created from Doxygen available at www.doxygen.org

the *Loki* library [77]. The *Loki::Functor* class was exactly what I wanted to create myself. Thus I created *cTimerMessageCB* by deriving from both *Loki::Functor* and my ubiquitous *cTimerMessage* class as shown in Listing A.6. Multiple inheritance is usually frowned upon except when the two parent classes have orthogonal behaviours that we want in one type. This is certainly the case here because we want to reuse the familiar interface of cTimerMessage so that the callback pattern is preserved and allowing the new cTimerMessageCB instantiations to cohabit peacefully with the old ones. Most of the new callback mechanisms in the code use cTimerMessageCB because we are in the phase of removing all the legacy cTimerMessage implementations to reduce maintenance and ease the learning curve.

I will give two examples of its use to show the full flexibility and ease with which it can be used. Show my sendUnsolNgbrAd and also Steve's wireles... that show both member func with diff arg and also glob func which is in my sendBURetranstimer.

A.3.3 Lifetime Management of Conceptual Data Structures

There are many different types of entries in the CDS described in both IPv6 and MIPv6 that require lifetime management i.e. any references to them need to be removed from the node and whatever resource the entry held needs to be released when its lifetime has expired. Examples of such entries are prefix and binding cache entries. Because of the memory overhead of having a particular timer message represent each entry a better method was to use one timer for each type of entry on each node. This required that the entries be sorted so that the timer is triggered for the earliest to expire entry. Once that entry expires whatever custom behaviour is needed for that entry needs to be run i.e. removal of the neighbour cache entries that refer to the expired router. Followed by rescheduling the timer for the next earliest to expire entry. Originally there were many different implementations for each type of entry. We knew that this was getting out of hand due to the many slightly different variations and constant code duplication and re-elimination of bugs for the different types of entries. So I decided on unifying all the common bits and using callbacks and templates to allow for custom behaviour that is unique to each type of entry. The result of this is the *ExpiryEntryList* class.

The sorting of the expired lifetimes was done using a heap sort algorithm as that was the most efficient considering the type of insertions that made are frequent and the value of the expired lifetime varied in a uniform manner.

A.3.4 Pointer Management

Most objects in the simulation are created dynamically and hence you end up with pointers to them. Because of the many complex relationships that exist for example in the CDS there are many pointers that refer to other pointers. This becomes a serious problem when you consider removing an entry requires looking through all the dependents to remove the reference to them. You can not guarantee that this is done correctly all the time. At other times you really need to share a pointer

Listing A.6: **cTimerMessageCB** Callback method of choice

```
extern const double SELF_SCHEDULE_DELAY;
extern const double ZERO_WAIT_DELAY;
#include "cTimerMessage.h"
#include <Loki/Functor.h>
#include <Loki/HierarchyGenerators.h> namespace Loki
{template < typename R, class TList = NullType,
           template <class> class ThreadingModel = DEFAULT_THREADING>
 class cTimerMessageCB:public cTimerMessage,
                       public Functor<R, TList, ThreadingModel>
 {
 public:
   typedef typename Functor<R, TList, ThreadingModel>::ParmList ParmList;
   template <class PtrObj, typename MemFn>
   cTimerMessageCB(const int& message_id, cSimpleModule* module,
                   const PtrObj& p, MemFn memFn, const char* name)
     :cTimerMessage(message_id, module, name), Functor<R, TList, ThreadingModel>(p,
     memFn)
     {}
   template <typename Fun>
   cTimerMessageCB(const int& message_id, cSimpleModule* module,
                   Fun fun, const char* name)
     :cTimerMessage(message_id, module, name), Functor<R, TList, ThreadingModel>(fun)
     {}
   virtual void callFunc()
     { compileTimeDispatch(Int2Type< Loki::TL::Length<ParmList>::value >());
     }
       Loki::Tuple< ParmList> args;
 private:
   void compileTimeDispatch(Int2Type<0>)
     {
       (*this)();
     }
   void compileTimeDispatch(Int2Type<1>)
     {
       (*this)(Field<0>(args));
     }
   void compileTimeDispatch(Int2Type<2>)
     {
       (*this)(Field<0>(args), Field<1>(args));
     }
   void compileTimeDispatch(Int2Type<3>)
     {
       (*this)(Field<0>(args), Field<1>(args), Field<2>(args));
     }
   void compileTimeDispatch(Int2Type<4>)
     {
       (*this)(Field<0>(args), Field<1>(args), Field<2>(args), Field<3>(args));
      }
  };
};
```

Listing A.7: **ExpiryEntryList** class used in management of entries' lifetimes

```
template <class Entry, class Timer = Loki::cTimerMessageCB<
//Return type of callback
typename Loki::Select< Loki::TypeTraits<Entry>::isPointer, Entry, void>::Result,
//Arguments to callback
typename Loki::Select< Loki::TypeTraits<Entry>::isPointer, Loki::NullType, TYPELIST_1(int
    )>::Result
> >
class ExpiryEntryList
{
  ExpiryEntryList(cSimpleModule *module, unsigned int timerId = TMR_ENTRYEXPIRED,
      bool relative = false);
  ExpiryEntryList(Timer* tmr, bool relative = false);
  ~ExpiryEntryList(void);

  void addEntry(Entry newEntry);
  void removeExpiredEntry(int);
  Entry removeExpiredEntry(void);
  void removeEntry(Entry &target);

  bool empty(void);
  bool findEntry(Entry &target);

  bool smallestExpiryEntry(Entry &smallest);
  void printList(void);

private:

  //Function object for heap comparison
  struct greaterExpiryTime : public std::binary_function<Entry, Entry, bool>
  {
    bool operator()(const typename Loki::Select< Loki::TypeTraits<Entry>::isPointer, void
     *, Entry>::Result& lhs, const Entry& rhs) const
      {
        return (lhs.expiryTime() > rhs.expiryTime());
      }
    bool operator()(const Entry lhs, const typename Loki::Select< Loki::TypeTraits<Entry
     >::isPointer, Entry, void*>::Result rhs) const
      {
        return (lhs->expiryTime() > rhs->expiryTime());
      }
  };

  simtime_t expiryTime(Entry e, Loki::Int2Type<true>) const
  {
    return e->expiryTime();
  }
  simtime_t expiryTime(const Entry& e, Loki::Int2Type<false>) const
  {
    return e.expiryTime();
  }

  Timer* entryExpiredNotifier;
  typedef typename std::vector<Entry> EntryList;
  EntryList entries;
  bool relative;
};
```

between many other objects and no one object owns it. Destroying a dependent should not entail also destroying the shared object otherwise you are left with a dangling reference at the other dependents. To make it easier to find the source of these problems in the first place and solve it for the second case requires the use of a reference counted smart pointer available in the `<boost/shared_ptr.hpp>` header of the Boost library [78].

The dependents that share the pointer will have a reference it through the *shared_ptr* while other dependents that nominally depend on it should refer to the pointer using the *weak_ptr* type. When a *shared_ptr* instance goes out of scope the reference count reduces by one. Eventually when the last dependent that shares the pointer goes out of scope the reference count becomes zero and the actual pointer that it holds is freed. Other dependents that used a *weak_ptr* to refer to it will automatically have their pointers set to zero, thus any unchecked uses of *weak_ptr* when the pointee has been destroyed will result in a segmentation fault at the site of the problem rather than some time later at a totally unrelated spot which is a classical symptom of the nefarious dangling reference problem.

Another type of smart pointer provided by the standard C++ library is *auto_ptr* [61]. It is useful for simple module's that use the **handleMessage** format because of the potentially many exit points. Every time a **return** statement is inserted you have to remember to **delete** the pointer in order to prevent memory leaks. By using an *auto_ptr* you are freed from having to call delete which makes the code concise and look much cleaner. You have to call **release** when you pass the pointer into OMNeT++ API calls otherwise segmentation faults will occur. If you follow the simple convention to wrap the nude pointer[6] in an *auto_ptr* and use that pointer through only the *auto_ptr* then this problem cannot arise because the compiler will complain bitterly about passing the wrong type into an OMNeT++ function call.

[6] the argument to **handleMessage**

Appendix B

Configuration of Simulation

B.1 XML Configuration

B.1.1 local element

mobileIPv6Support For routers set to on in order to use the reduced unsolicited RA intervals and the addition of the router advertising interval option as defined in the MIPv6 draft. For hosts this enables CN support for route optimisation.

mobileIPv6Role HomeAgent for router to server as HA. MobileNode for hosts to serve as MN. Default is None so it behaves like a CN.

hierarchicalMIPv6Support Turns on MN support to register with a MAP. For routers this attribute does not have an effect unless the map attribute is also on. By default all routers will forward MAP options when simulation is built with BUILD_HMIP

map For router will enable serving as a MAP. It should advertise itself by specifying its global address at ./interface/AdvertiseMapList element for the interfaces that it should serve as MAP on.

B.2 Libcwd Diagnostic Message Streams

Libcwd [70] is integrated into IPv6Suite when the option LIBCWD_DEBUG is turned on in CMake as shown in Figure B.1. It is a library that allows an arbitrary number of levels or "channels" to be assigned to each debug message. This is done in the Dout macro call. When LIBCWD_DEBUG in CMake is off (the default setting) the simulation will no longer depend on Libcwd and all Dout calls are ignored during compilation, without the use of allows others to use the simulation without having to install Libcwd too.

Listing B.1: XML configuration file used in Section 5.3

```
//

<netconf debugChannel="debug1.log:MobileMove::notice:custom:Ping6:Statistic">
<!--
  MIPv6MissedAdv:HMIPv6:AddrResln:MIPv6:AddressTimer:RouterDisc:Forwarding:NeighbourDisc:debug">
-->
<local node="client1" mobileIPv6Support="on" mobileIPv6Role="MobileNode" hierarchicalMIPv6Support="off">
 - <interface name="wlan0" HostDupAddrDetectTransmits="0">
    - <WirelessEtherInfo>
        <WEInfo WETxPower="0.1"/>
      </WirelessEtherInfo>
   </interface>
</local>
<local node="server4" mobileIPv6Support="on">
   <interface name="eth0"></interface>
</local>
<!--
   four in total. The rest have been removed to save space
-->
<local node="ap1">
 - <interface name="wlanap">
    - <WirelessEtherInfo>
        <WEInfo WETxPower="0.1"/>
      </WirelessEtherInfo>
   </interface>
</local>
<local node="ha" routePackets="on" mobileIPv6Support="on" mobileIPv6Role="HomeAgent">
 - <interface name="eth0" AdvSendAdvertisements="on" AdvHomeAgent="on" MaxFastRAS="10">
      <inet_addr>3018:FFFF:0:0:127b:c0ff:fe2e:7212</inet_addr>
    - <AdvPrefixList>
        <AdvPrefix AdvOnLinkFlag="on" AdvRtrAddrFlag="on">3018:FFFF:0:0:127b:c0ff:fe2e:7212/64</AdvPrefix>
      </AdvPrefixList>
   </interface>
 - <interface name="eth1" AdvSendAdvertisements="on" MaxFastRAS="10">
      <inet_addr>3018:FFFF:0:1:606:98ff:fe24:52f5</inet_addr>
    - <AdvPrefixList>
        <AdvPrefix AdvOnLinkFlag="on" AdvRtrAddrFlag="on">3018:FFFF:0:1:606:98ff:fe24:52f5/64</AdvPrefix>
      </AdvPrefixList>
   </interface>
 - <interface name="eth2" AdvSendAdvertisements="on" MaxFastRAS="10">
      <inet_addr>3018:FFFF:0:2:8087:eff:fe1a:7281</inet_addr>
    - <AdvPrefixList>
        <AdvPrefix AdvOnLinkFlag="on" AdvRtrAddrFlag="on">3018:FFFF:0:2:8087:eff:fe1a:7281/64</AdvPrefix>
      </AdvPrefixList>
   </interface>
 - <interface name="eth3" AdvSendAdvertisements="on" MaxFastRAS="10">
      <inet_addr>3018:FFFF:0:3:5f6a:a9ff:fe2c:df2e</inet_addr>
    - <AdvPrefixList>
        <AdvPrefix AdvOnLinkFlag="on" AdvRtrAddrFlag="on">3018:FFFF:0:3:5f6a:a9ff:fe2c:df2e/64</AdvPrefix>
      </AdvPrefixList>
   </interface>
 - <interface name="eth4" AdvSendAdvertisements="on" MIPv6MaxRtrAdvInterval="1.4" MaxFastRAS="10">
      <inet_addr>3018:FFFF:0:4:5f6a:a9ff:fe2c:df2f</inet_addr>
    - <AdvPrefixList>
        <AdvPrefix AdvOnLinkFlag="on">3011:BBBB:3333:6666:5f6a:a9ff:fe2c:df2f/64</AdvPrefix>
      </AdvPrefixList>
   </interface>
   <!-- routing table configuration -->
 - <route>
      <routeEntry routeIface="eth0" routeDestination="3018:FFFF:0:0:0:0:0:0/64"/>
      <routeEntry routeIface="eth1" routeDestination="3018:FFFF:0:1:0:0:0:0/64"/>
      <routeEntry routeIface="eth2" routeDestination="3018:FFFF:0:2:0:0:0:0/64"/>
      <routeEntry routeIface="eth3" routeDestination="3018:FFFF:0:3:0:0:0:0/64"/>
      <routeEntry routeIface="eth4" routeDestination="3011:BBBB:3333:6666:0:0:0:0/64"/>
   </route>
</local>
<misc>
 - <ObjectMovement>
    - <MovingNode NodeName="client1" startTime="0">
        <move moveToX="352" moveToY="378" moveSpeed="3"/>
        <move moveToX="88" moveToY="118" moveSpeed="3"/>
      </MovingNode>
   </ObjectMovement>
</misc>
```

The debug channels can be turned on or off, controlling the amount of information in the log file. I have added support for specifying both the log file where the output of Dout messages go to and the channels to be enabled in the *debugChannels* attribute of the netconf element in the XML configuration file as depicted in Listing B.1. The value of this attribute is a colon separated list of strings. The first string is the filename of the libcwd log file. The rest of the strings are the debug channels that will be enabled. The filename will have the process id of the simulation appended. To use the same log file for all instances of the simulation append the number 1 into the name and it will not append a process id number thus overwriting the contents of the file every time the simulation is executed.

B.3 CMake - Cross-Platform Build Configuration Tool

CMake [79] is a cross-platform Makefile generator that is easy to learn and use. Initially we tried delving into GNU *Autoconf* but looking at the manual and examples were enough to convince us that it was difficult to learn. I set out looking for a build tool which was almost as flexible as Autoconf but without the deep learning curve. CMake was to the best of my knowledge the Makefile generator that is the easiest to use, and learn[1] and was mature for C++ software projects. While it is not perfect and in future I hope there are better tools as some of the CMakeLists.txt files in IPv6Suite are quite verbose and complex. It is relatively easier to write complex build options compared to Autoconf and has cross platform abilities. Figure B.1 is a screenshot of CMake's `ccmake`, a Unix command line user interface to change the settings of the build for the various configurations that were tested in the Chapter 5.

Feature	**IPv6Suite CMake Build Option**
MIPv6	BUILD_MOBILITY
Optimistic Duplicate Address Detection	JLAI_ODAD
link up trigger	EWU_L2TRIGGER
Fast Solicited Router Advertisement	JLAI_FASTRA
HMIPv6	BUILD_HMIP

Table B.1: Features compiled into simulation and the corresponding IPv6Suite build option

Table B.1 shows the list of features offered by IPv6Suite and their build options. Some build options like BUILD_HMIP require other build options as a prerequisite and I have been able to enforce these requirements as error messages in `ccmake`. If the user ignores the warning then generation of the Makefiles does not occur. Some build options require extra configuration in the XML configuration file for the

[1]Took me about 6 hours to build the initial set of CMakeLists.txt for IPv6Suite with shared libraries support and selective compilation of files. The initial build system inherited from IPSuite just built everything statically and linked it all together and used up lots of hard drive space

```
                                                    Page 1 of 2

 BOOSTROOT                         /usr/include
 BUILD_DEBUG                       ON
 BUILD_DOCUMENTATION               ON
 BUILD_HMIP                        OFF
 BUILD_MOBILITY                    ON
 BUILD_SHARED_LIBS                 ON
 BUILD_TESTING                     ON
 BUILD_UNITTESTS                   OFF
 CMAKE_BACKWARDS_COMPATIBILITY     1.8
 CMAKE_INSTALL_PREFIX              /usr/local
 COMPILER_WARNINGS                 -Wall
 CPPUNIT_CONFIG                    /usr/bin/cppunit-config
 EWU_L2TRIGGER                     OFF
 EWU_MACBRIDGE                     OFF
 JLAI_FASTRA                       ON
 JLAI_ODAD                         OFF
 LIBCWD_DEBUG                      ON

EWU_L2TRIGGER: Link up Trigger for MIPv6
Press [enter] to edit option                        CMake Version 1.8 - patch 1
Press [c] to configure
Press [h] for help         Press [q] to quit without generating
Press [t] to toggle advanced mode (Currently Off)
```

Figure B.1: Screenshot of `ccmake` on IPv6Suite

build option to take effect during simulation execution for example, JLAI_FASTRA, BUILD_MOBILITY and BUILD_HMIP. The only exceptions are JLAI_ODAD and EWU_L2TRIGGER that affect all MNs for now, but it is easy to add support for runtime options that enable them on a per mobile node basis or interface basis for JLAI_ODAD and EWU_L2TRIGGER respectively. Thus by mixing and matching these options you can build IPv6Suite for each simulation scenario evaluated in Chapter 5.

Appendix C

Interpretation of Box Plot

Box plots provide a summary of the distribution of the sampled data. While they do not reveal as many features as histograms do, like whether more than one modality[1] exists [65], they can show the center and spread of data. The box in the box plot as shown in Figure C.1 has a horizontal line in the middle that represents the median. The top and bottom horizontal lines of the box, called "hinges" represent the third and first quartile[2] respectively. The box plot can also be in landscape orientation as shown in Figure 6.10. A line extends from each hinge known as a whisker reveals the existence of data that is within $1.5IQR$, where Inter-Quartile Range (IQR) is simply the range from the 1st to the 3rd quartile. Any data values beyond the range of the wiskers are considered outliers and are depicted as plain dots or open circles as shown in this publication. I have chosen to use the box plot because it is much easier to see at a glance which handover scheme is better, and reveals many characteristics the symmetry, degree of spread, and the presence of outliers. Some plots as shown in Figure 6.3 and Figure 6.4 have a bidirectional arrow with a dot in the middle overlaid on the box. The dot represents the sample mean and the end point of the arrow is the standard deviation.

[1] A normal curve only has one peak

[2] a quartile is the value at which a quarter of the observed values are below it

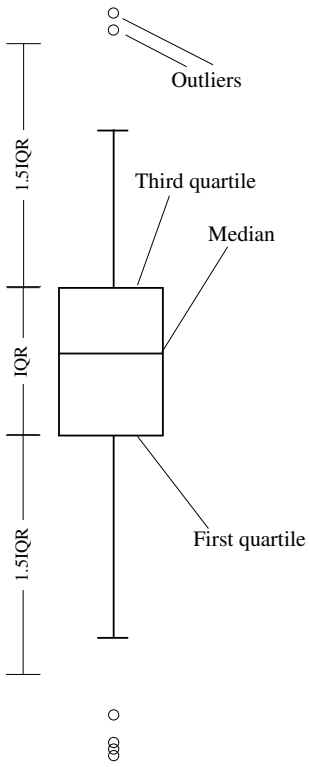


Figure C.1: Diagram of a box plot showing main features

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